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STORM-SURGE FORECASTING

by

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FOREWORD

Accurate prediction of storm surge is vital for purposes of planning precautionary measures to be taken by DOD coastal installations. The probability that a storm surge will affect a port to any significant extent is also essential for a realistic assessment of the degree of shelter afforded by a harbor, and may constitute an important consideration in deciding whether fleet units should sortie or remain in port.

This publication represents an adaptation, prepared by Mr. J. W. Nickerson, of a unique storm-surge forecasting technique developed by Dr. C. P. Jelesnianski. This technique results in a computed storm surge profile at the inner boundary of an artificial standard basin seaward of the coast. The profile is derived from nomograms based upon a standard storm passing over a standard basin. Thumb rules and guidelines are presented in this publication for subjectively modifying the computed storm surge height as it moves shoreward of the artificial basin boundary, to fit the natural conditions of a particular coastline.

Major advantages of this system are its applicability to almost any locale, its adaptability to data normally available to the field forecaster and the speed with which the forecast may be modified to remain current with natural fluctuations of the storm.

An extensive bibliography is furnished, in addition to references cited in the text, for those who require much deeper understanding of this phenomena.

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TABLE OF CONTENTS

	Page
FOREWORD	i
TABLE OF CONTENTS	iii
LIST OF FIGURES	v
1. INTRODUCTION	1
1.1 Jelesnianski Technique	1
1.2 The Jelesnianski Model	2
1.3 Operational Applicability	3
2. STORM-SURGE PARAMETERS AND DEFINITIONS	4
2.1 Prediction Parameters	4
2.2 Standard Storm and Basin	7
2.3 Storm-Surge Parameters	9
3. FORECASTING THE STORM SURGE	11
3.1 Determining the Precomputed Storm-Surge Parameters for a Standard Storm Over a Standard Basin	11
3.2 Correcting the Precomputed Storm Surge for Actual Storms and Basins	22
3.3 Factors to Be Considered in Projecting Water-Level Forecasts Inland From the Straight, 15-Ft. Deep, Inner, Standard-Basin Boundary	26
3.4 Some Thumb Rules to Aid in Storm-Surge Forecasting	32
BIBLIOGRAPHY AND REFERENCES	36
APPENDIX A. FORECAST CHECK-OFF LIST AND SAMPLE STORM-SURGE PREDICTION FOR LANDFALLING TROPICAL CYCLONES	A-1
1. Storm-Surge Forecast Check-Off List -- Landfalling Tropical Cyclones	A-1
2. Sample Forecast for a Hurricane Landfalling on an Island Chain and the Effects on an Enclosed Body of Water	A-5
3. Sample Forecast for a Hurricane Landfalling on a Low Coast and River Delta	A-12

TABLE OF CONTENTS (Continued)

		Page
APPENDIX B.	FORECAST CHECK-OFF LIST AND SAMPLE STORM-SURGE PREDICTION FOR NON-LANDFALLING TROPICAL CYCLONES	B-1
	1. Storm-Surge Forecast Check-Off List -- Non-Landfalling Tropical Cyclones	B-3
	2. Sample Forecast for a Non-Landfalling Hurricane	B-5
APPENDIX C.	FORECAST CHECK-OFF LIST AND SAMPLE STORM-SURGE PREDICTION FOR EXTRATROPICAL STORMS	C-1
APPENDIX D.	DEPTH PROFILE CORRECTION FACTORS	D-1

LIST OF FIGURES

Page

Figures (34):

1. The Pressure Drop $\overline{P}$ of the Storm Is the Mean Sea-Level Pressure Difference in Millibars Between the Pressure at the Center p_0 and the Pressures at Points Where Storm-Associated Isobars Turn Anticyclonic (points p_1, p_2, p_3) 5
2. Crossing Angles Relative to Storm Movement With Respect to the Coast 6
3. Wind Field of a Tropical Cyclone That Conforms Closely to Standard Storm Conditions (windspeed in knots) 7
4. The Standard Basin Defined by Jelesnianski 8
5. The Storm-Surge Profile Indicates the Height That the Water Will Attain at Various Distances From the Peak-Surge Point Along the Coast at the Time of Landfall 10
6. The Directly Generated Surge Is the First Crest and Trough of the Storm Surge 10
7. Contours of Distance in Nautical Miles From the Landfall Position to the Point of Peak Surge to the Right Along the Coast, as Observed From Seaward 13
8. Contours of Peak-Surge Values in Feet for a Standard Storm at the Inner Standard-Basin Boundary 14
9. Same as Figure 8 for the Minimum Surge Portrayed at the Time of Peak Surge 15
10. Contours of Distance Along the Inner Standard-Basin Boundary, in Nautical Miles, From the Point of Peak Storm Surge to the Point of 1/2 the Peak-Surge Height to the Right of Landfall (as seen from seaward) (after Jelesnianski [44]) 16
11. Contours of Distance Along the Inner Standard-Basin Boundary, in Nautical Miles, From the Point of Peak Storm Surge to the Point of 1/2 the Peak-Surge Height to the Left of Landfall (as seen from seaward) (after Jelesnianski [44]) 17

		Page
12.	Contours of Distance Along the Inner Standard-Basin Boundary, in Nautical Miles, From the Point of Peak Storm Surge to the Point of 1/4 the Peak-Surge Height (after Jelesnianski [44])	18
13.	Distance Along the Inner Standard-Basin Boundary Between the Peak Surge and the Zero Surge (after Jelesnianski [44])	19
14.	Distance Along the Inner Standard-Basin Boundary Between the Peak Surge and the Minimum Surge (after Jelesnianski [44])	20
15.	Arrival Time, in Minutes, of Peak Surge at the Inner Standard-Basin Boundary After Landfall	21
16.	Determination of the Wind Field Correction Factor V_R From the Radius of Maximum Wind in Nautical Miles and Pressure Drop	23
17.	Correction Factors at Selected Points Along the Eastern Seaboard of the United States for Depth Profiles Other Than Standard	25
18.	Correction Factors at Selected Points Along the Gulf States and Florida	25
19.	Departures of the Observed Daily Mean-Sea Level From the Predicted Astronomical Tide for Selected Coast and Geodetic Survey Tide Stations, 1957	27
20.	The Effect of Wind Stress Upon Inshore Waters	29
21.	Extensive Flooding Can Occur From Wind Stress if the Water Level Tops the Dunes and the Back Shore Is Moderately Flat	29
22.	With Mountainous Waves and Surf, as Generated by a Mature Tropical Cyclone, the Incoming Water in the Surf Zone Is in Excess of That Which Can Drain Back by Gravity	30

LIST OF FIGURES (Continued)

		Page
23.	Barrier Islands Can Also Act as a Barrier to Water Flowing Back to the Ocean	30
A-1.	Hurricane DONNA 1960, September 9-13. Synotpic Charts (after Harris [30])	A-6
A-2.	Hurricane DONNA 1960, September 9-13. High Water Mark Chart for Florida	A-7
A-3.	Hurricane AUDREY 1957, June 26-27. Topography of Southern Louisiana (after Harris [30])	A-13
A-4.	Hurricane AUDREY 1957, June 26-27. Synoptic Charts (after Harris [30])	A-15
A-5.	Hurricane AUDREY 1957, June 26-27. High Water Mark Chart for Texas and Western Louisiana	A-16
A-6.	Hurricane AUDREY 1957, June 26-27. High Water Mark Chart, Eastern Louisiana	A-17
B-1.	For Storms Paralleling the Coast the Precomputed Height of the Directly Generated Surge Is Determined by Entering the Nomogram: (1) With the Closest Point of Approach (CPA) Along the Abscissa, (2) Moving Vertically Above and Below the CPA Line to the Storm Speed of Motion and (3) Reading the Height of the Crest (above) and the Trough (below) of the Directly Generated Surge Height for the Standard Storm h_s (after Jelesnianski [44])	B-2
B-2.	Hurricane DONNA 1960, September 9-13. Storm-Surge Chart (after Harris [30])	B-6
C-1.	Wind Induced Wave Set-Up at Atlantic City (after Miller [56])	C-2
C-2.	Extratropical Storm	C-4
C-3.	Storm Surge at Atlantic City, 5-7 November 1953	C-5
D-1.	Slope Profiles With Correction Factors for Selected Gulf Coast Points	D-3

LIST OF FIGURES (Continued)

		Page
D-2.	Slope Profiles With Correction Factors for Selected Gulf Coast Points	D-4
D-3.	Slope Profiles With Correction Factors for Selected U.S. Southern Atlantic Coast Points	D-5
D-4.	Slope Profiles With Correction Factors for Selected U.S. Southern Atlantic Coast Points	D-6
D-5.	Slope Profiles With Correction Factors for Selected U.S. Middle Atlantic Coast Points	D-7
D-6.	Slope Profiles With Correction Factors for Selected U.S. Middle Atlantic Coast Points	D-8
D-7.	Depth Profile Correction Factors for Republic of Vietnam	D-9
D-8.	Slope Profiles With Correction Factors for Selected Points Along the Southern Republic of Vietnam Coast	D-10
D-9.	Slope Profiles With Correction Factors for Selected Points Along the Northern Republic of Vietnam Coast	D-11

1. INTRODUCTION

When a tropical cyclone or an intense extratropical storm approaches a coastline, there is a resulting rise in the water level which may permit surf to penetrate far inland of the normal high-water mark. This abnormal rise in the water level is defined as storm surge, and is caused by wind stress on the water surface and the effects of atmospheric pressure reduction.

Storm surge is also called storm tide, storm wave, tidal wave or hurricane wave. The words "wave" or "tide", however, imply a periodic motion, and as such are misnomers when used to describe a surge. The surge is a single abnormality of the water level directly associated with the storm, and may take several days to pass. Tides have a period of hours, and are superimposed upon the surge. Waves have a period of seconds, and are superimposed on both tides and surges. All of these are important to understanding and predicting the water-level variations which occur on the occasion of a surge.

1.1 Jelesnianski Technique

Among the many methods devised for making storm-surge forecasts, a technique developed by Jelesnianski [43, 44] is operationally unique in that it uses precomputed nomograms which almost entirely eliminate laborious mathematical calculations and requires only facilities and data readily available to the forecaster. This technique shows skill in

forecasting the basic storm surge, within certain well-defined limitations, and is set forth herein in all significant detail. The basic input data needed to apply the Jelesnianski technique are storm speed, direction of storm movement with respect to orientation of the coastline, the distance (radius) from storm center to the point of maximum winds, the storm central pressure and, of course, the bathymetry of coastal waters near the point of landfall or nearest approach to the coast. Output values are water height versus distance left and right along the coast relative to the storm's position.

1.2 The Jelesnianski Model

The Jelesnianski technique is based upon first computing the storm-surge profile for a "standard storm" over a "standard basin", and then correcting these precomputed values for better agreement with the actual storm and basin by the use of another nomogram and a simple equation. The product of this method is a profile of storm-surge height along the inner basin boundary, which is an artificial, straight, inner boundary of the model at a water depth of 15 feet. This inner basin boundary is parallel to the coastline at the point where the storm center crosses the coast. The forecaster must then subjectively take into account such local effects as sea-level anomalies, wind stress, wave set-up and rain before issuing a forecast of the water-level heights expected at any specific point inshore from the inner basin boundary. These problems are discussed in detail in the following text and

appendices, along with sample forecasts for actual tropical cyclones and an extratropical storm.

1.3 Operational Applicability

The Jelesnianski nomograms are computer products based upon data accumulated from hurricanes over the continental shelf of the Gulf and East coasts of the United States. However, there is no known reason why this method should not be applicable to other areas of the world with similar coastal conditions. Consequently, appendix A provides an example of the interpolation of depth-correction factors for applicable coastal sections of the Republic of Vietnam, as a proposed storm-surge forecasting aid.

This publication provides forecasting thumb rules and guidelines for extending the forecasting procedure shoreward from the inner basin boundary and considers the variations of storm surge that may be expected for most topographic features of a coastline. The consideration is subjective and presupposes that the forecaster has studied not only the bottom topography from the normal high water mark to at least 50 miles at sea, but has also studied the topography of the shore inland from the beach.

In the final analysis, storm-surge forecasts prepared by any method can be no better than the accuracy with which the movement and the intensity of the storm itself are predicted. As will be shown by the examples in the appendices, this system can be applied quickly and easily to produce a skillful forecast.

2. STORM-SURGE PARAMETERS AND DEFINITIONS

2.1 Prediction Parameters

Wind and pressure are the forces which contribute to storm-surge generation. The extent to which wind stress and the pressure force are effective is related directly to the strength, size and motion of the storm with respect to the coastline. The pertinent parameters are:

(a) Landfall - The point where the center of the storm crosses the coastline.

(b) Pressure Drop of the Storm - The pressure difference in millibars from the center to the periphery of the storm (fig. 1). This is the most important storm parameter; it controls the peak surge on the coast.

(c) Radius of Maximum Winds - The distance in nautical miles from storm center to the radius at which surface winds are a maximum. If there is a band rather than a pronounced peak of maximum winds, then the distance to the outer edge should be used for this radius. This parameter controls the horizontal extent of the surge along the coast.

(d) Speed of the Storm - Speed of movement of the storm center. With all other parameters held fixed, there is a critical storm speed that gives the highest peak surge on the coast.

(e) Movement of the Storm - Direction of motion of the storm center. With all other parameters held fixed, there is a critical direction of storm motion relative to the coastline which gives the highest peak surge on the coast.

Throughout this paper, storm motion is considered as the direction from which a storm is moving relative to the coastline at the point where the eye (center) crosses the coastline. The observer is always considered to be at sea facing the coast normal to the point of crossing; that is, he

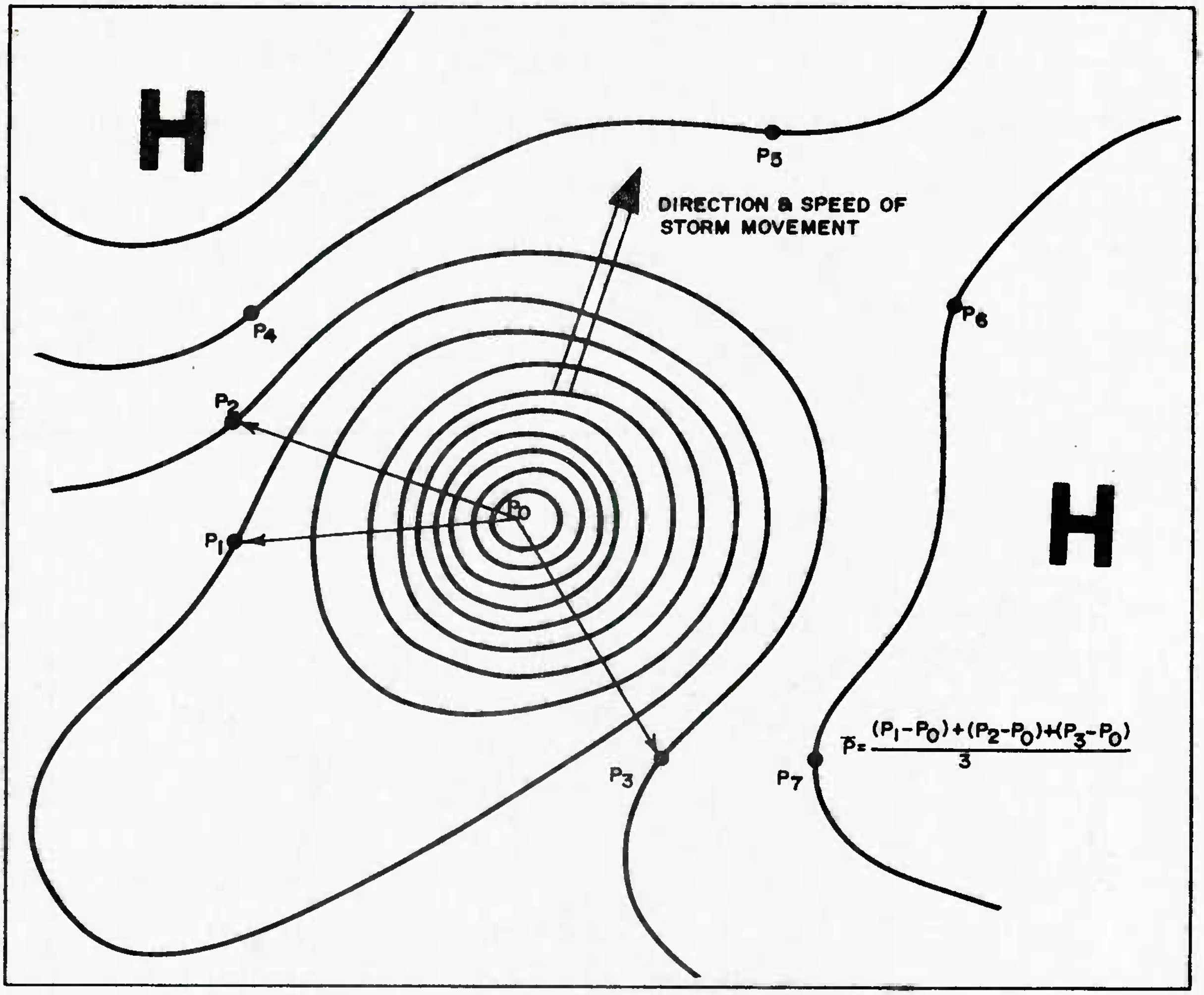


Figure 1. The Pressure Drop $\overline{P}$ of the Storm Is the Mean Sea-Level Pressure Difference in Millibars Between the Pressure at the Center P_0 and the Pressures at Points Where Storm-Associated Isobars Turn Anti-cyclonic (points P_1, P_2 and P_3). Points P_4, P_5, P_6 and P_7 Are Not Used, Since the Circulation There Is More Associated With Surrounding High-Pressure Areas Than the Storm.

is at the 090° relative position. Thus, a storm moving north-northwest, as indicated by the arrows in figure 2, would have a "crossing angle" of about 180° off Ft. Pierce, Florida; about 000° off Sarasota, Florida and about 090° as it approached the coast near Pensacola, Florida.

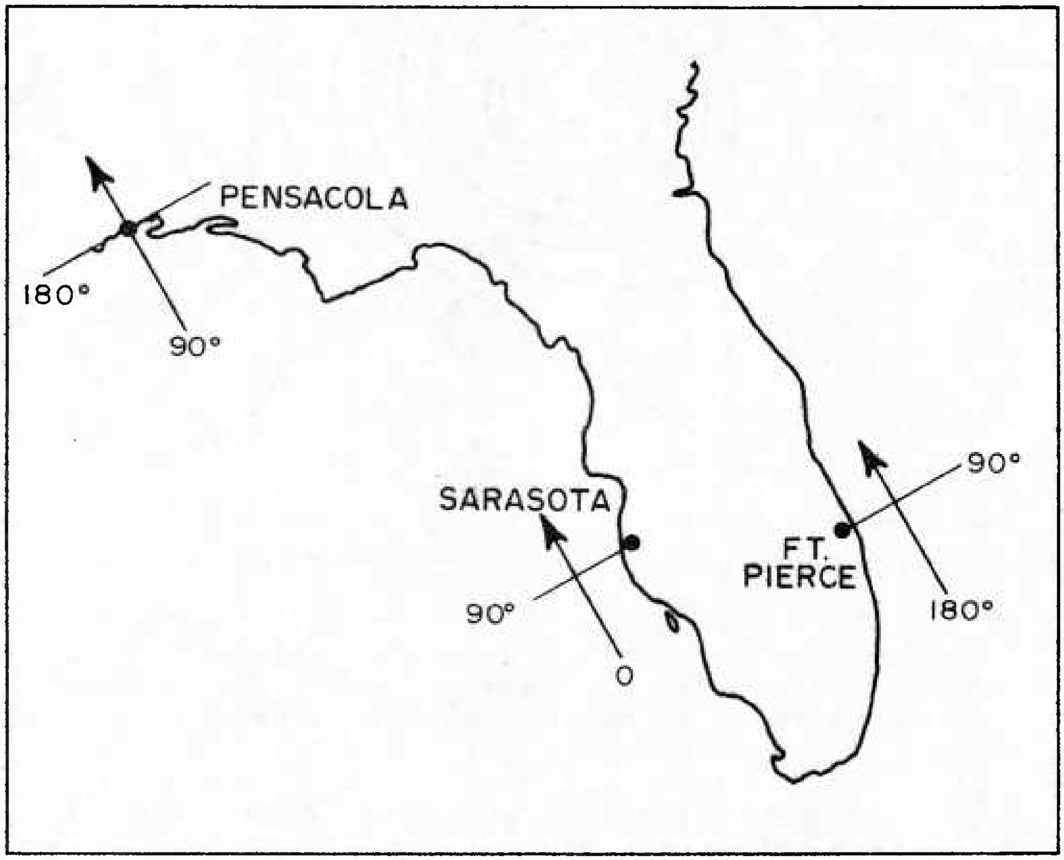


Figure 2. Crossing Angles Relative to Storm Movement With Respect to the Coast.

2.2 Standard Storm and Basin

The storm-surge forecasting technique presented in this paper is based upon the use of precomputed circular nomograms which are calculated for a "standard storm" over a "standard basin", defined as follows:

(a) Standard Storm - A model storm centered at 30° latitude, from which the precomputed circular nomograms for calculating the storm-surge height profile were developed. A "standard storm" has a Wind Field Correction Factor V_R of 87 knots. This factor is discussed in section 3.2 and is obtained from figure 16 using the radius of maximum wind and the Pressure Drop $\overline{P}$ of the storm. The storm surge height for natural storms that differ from the standard storm conditions is subsequently determined by the equation (1) in section 3.2. The storm surge is only mildly sensitive to latitude, varying less than 10 percent between 15° and 45° latitude. Figure 3 shows the wind field of a tropical cyclone that conforms closely to standard-storm conditions.

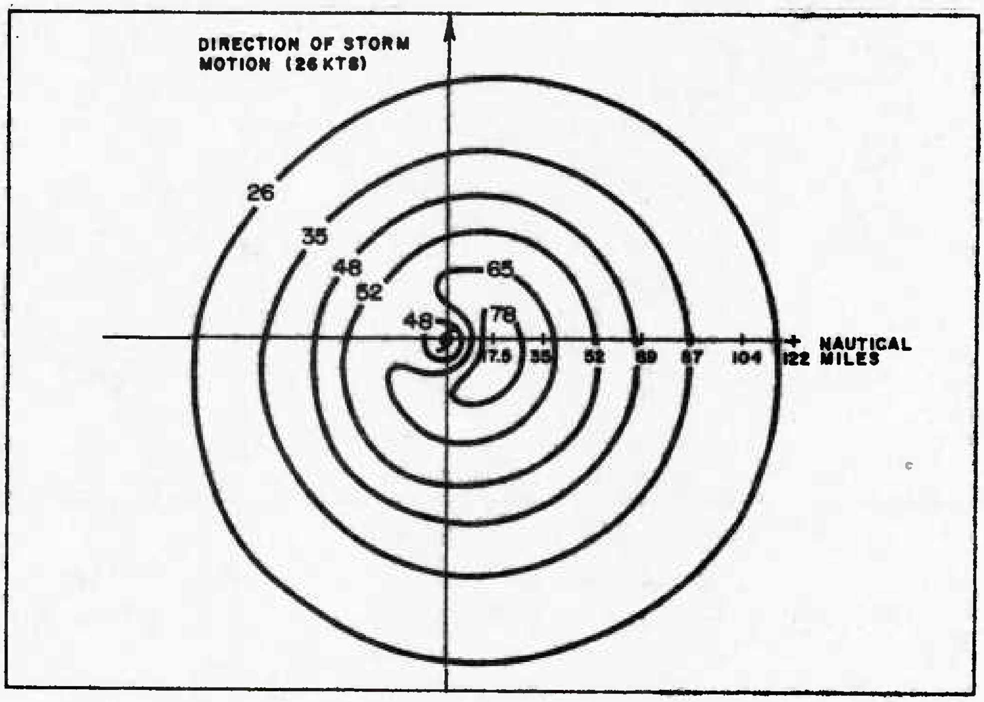


Figure 3. Wind Field of a Tropical Cyclone That Conforms Closely to Standard Storm Conditions (windspeed in knots).

(b) Standard Basin - The model basin from which the precomputed circular nomograms were developed has: a straight, inner (coastal) boundary represented by a vertical wall 15-feet deep; a linear, sloping, bottom profile which increases in depth at a rate of 3.45 feet per nautical mile seaward perpendicular to the coast; an open outer boundary with a depth of 195 feet at a distance 52 nautical miles seaward from the inner boundary; and open boundaries 520 miles apart at the two ends (see fig. 4). Differences between the depth profile of an actual basin and that of the standard basin are taken into account by means of a Depth Profile Correction Factor F_D, as described in section 3.2. Other differences between a natural basin and the standard basin are much more complex and must be treated subjectively, as discussed in section 3.3.

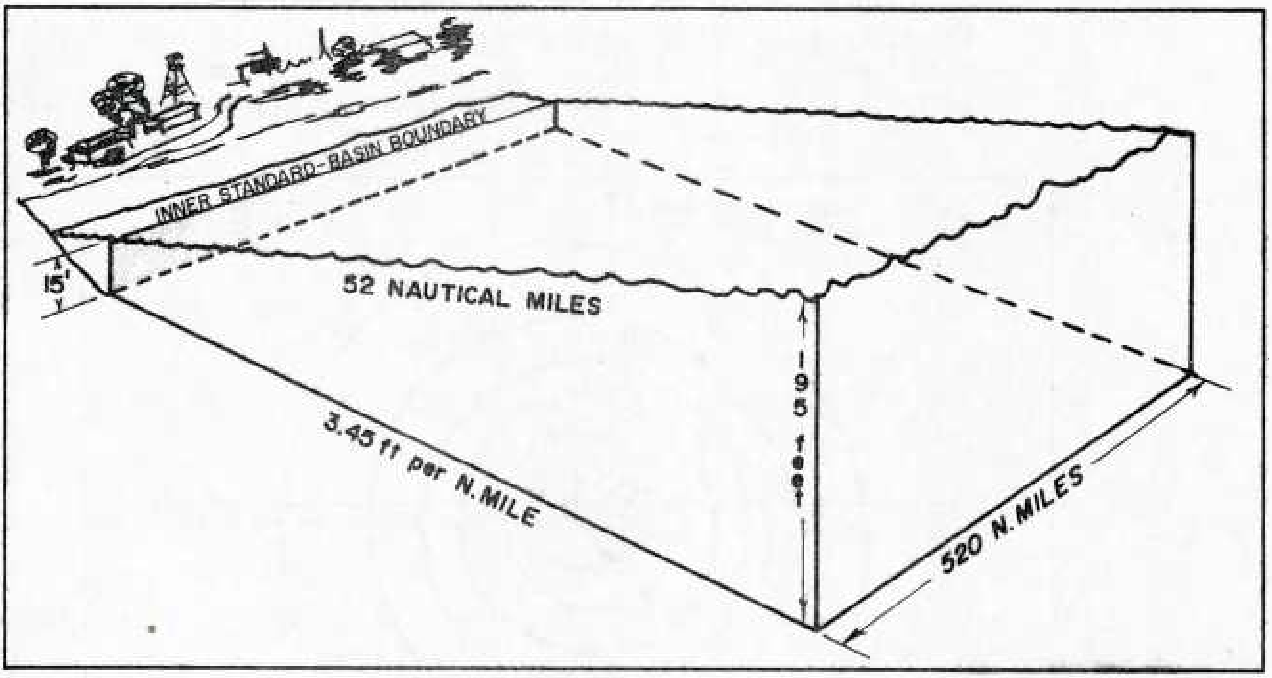


Figure 4. The Standard Basin Defined by Jelesnianski.

2.3 Storm-Surge Parameters

Other features related directly to the storm surge are defined as follows:

(a) Storm-Surge Profile - A plot of the maximum water-level heights reached at various points along the coastal boundary of the basin, as depicted in figure 5.

(b) Directly Generated Surge - The first crest and trough of any storm-surge profile associated with the storm's center, and moving with the storm, is the Directly Generated Surge. Storms traveling parallel to the coast can generate traveling and/or standing waves superimposed upon the storm-surge profile. Figure 6 illustrates that storms moving rapidly (35 knots or more) parallel to the coast can generate traveling waves which amplify a portion of the directly generated surge; i.e., storms moving along the coast with land to the left (crossing angles near 180°) amplify the directly generated trough, whereas storms moving along the coast with land to the right (crossing angles near 0°) amplify the directly generated crest. (The amplied crest and troughs are as compared to the storm-surge profile of a stationary storm.)

(c) Resurgences - In the case of storms moving nearly parallel to a coastline, large oscillations of the surge can occur during the period of storm approach and passage at any point along the coast. These oscillations, excluding the directly generated surge, are called resurgences (see fig. 6). Resurgences can be either shelf seiches or edge waves (Munk et. al. [60], Reid [80]). Shelf seiches also occur for slowly moving storms making landfall.

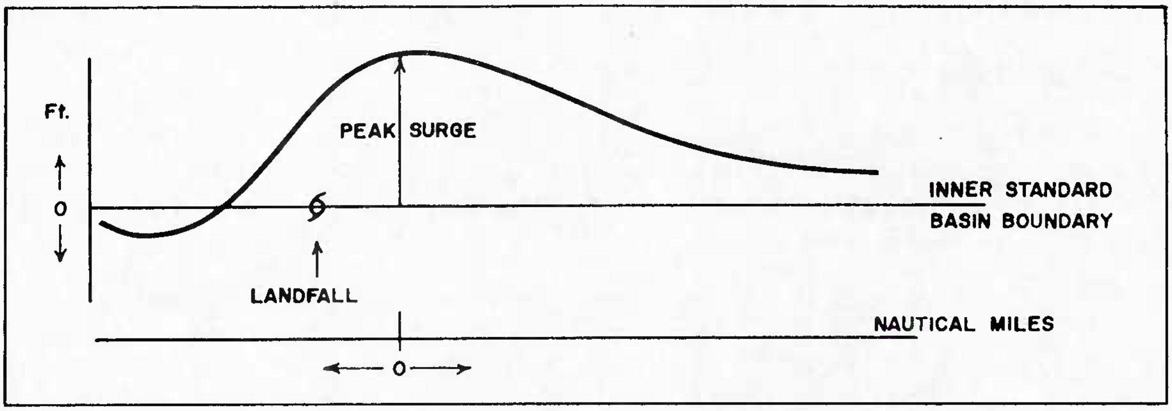


Figure 5. The Storm-Surge Profile Indicates the Height That the Water Will Attain at Various Distances From the Peak-Surge Point Along the Coast at the Time of Landfall.

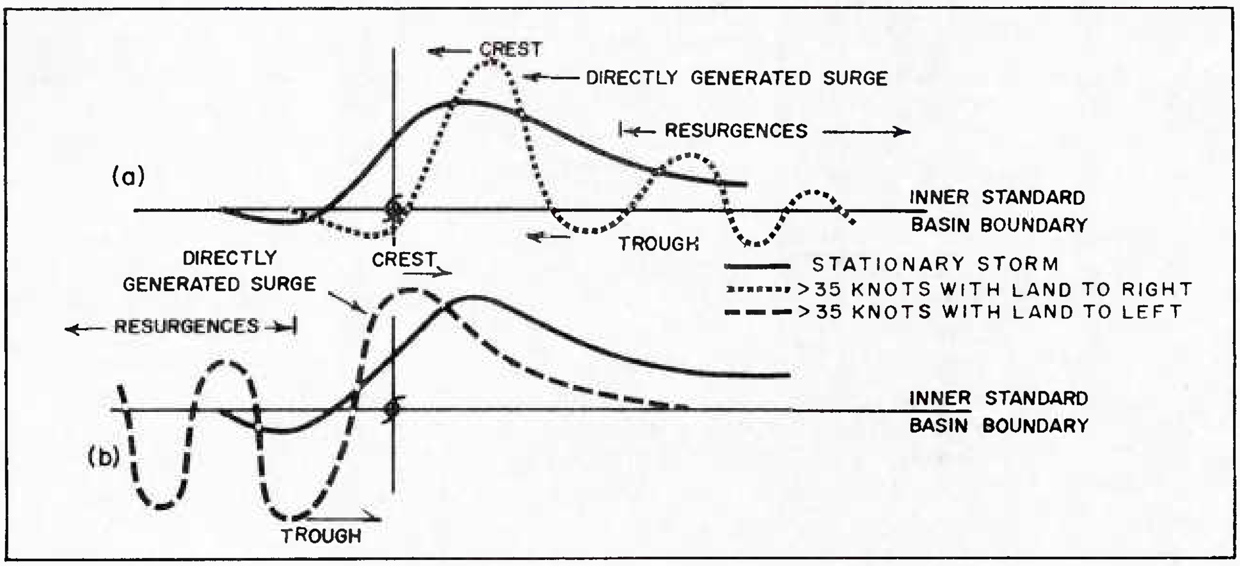


Figure 6. The Directly Generated Surge Is the First Crest and Trough of the Storm Surge. Crests and Troughs That Follow the Directly Generated Surge, if They Develop, Are Called Resurgences. Rapidly Moving Storms Which Parallel the Coast May Develop Travelling Waves Which (a) Amplify the Crest of the Directly Generated Surge if the Storm Is Moving Along the Coast to the Left With Land to the Right, or (b) Amplify the Trough of the Directly Generated Surge if It Is Moving Along the Coast to the Right With Land to the Left.

3. FORECASTING THE STORM SURGE

The nomograms for preparing a storm-surge prediction are presented in this chapter. Forecasting check-off lists and sample storm-surge predictions for a landfalling tropical cyclone are contained in appendix A, for non-landfalling tropical cyclones in appendix B, and for extratropical storms in appendix C.

3.1 Determining the Precomputed Storm-Surge Parameters for a Standard Storm Over a Standard Basin

To facilitate solution of the complex equations involved in calculating the various storm-surge parameters, this technique assumes a standard storm over a specified standard basin. The results are the basic circular nomograms, figures 7 to 15, which are used to construct the precomputed storm-surge profile. Reference must then be made as discussed in section 3.2 to an additional nomogram, figure 16, and equation (1) to modify the precomputed storm-surge profile in order to arrive at the storm-surge prediction for an actual storm over a natural basin. At this point, consideration must subjectively be given to such complex inshore factors as are described in section 3.3 before the predicted storm-surge height can be determined.

To determine the parameters of the precomputed storm-surge profile for a standard storm, enter figures 7 through 15 with the following forecast parameters for the actual storm: the angle at which the storm will cross the coastline; the

speed of storm movement; and the radius of maximum wind. Storm crossing angles with respect to the coast are indicated by rays in these figures, and storm speed from 0 to 50 knots by radii. The nomograms marked (a) and (b) in each figure are for use with storms having a 15- to 30-nautical mile radius of maximum winds, respectively. The radius of maximum winds controls the horizontal extent or dispersion of the storm surge along the coast. Interpolation should suffice in the event the actual radius of maximum winds is different from the precomputed values of 15 and 30 nautical miles.

The height of the storm surge at various distances from the peak storm surge may be deduced from figures 7 to 15. If these values are plotted in some appropriate scale along the inner basin boundary, a cross section of the storm surge or the precomputed storm-surge profile for a standard storm over a standard basin is produced.

The region of dashed lines in figure 8 and 9 directs attention to those cases of direction and speed of storm movement with respect to the coast where the edge-wave resurgence phenomena illustrated in figure 6 are to be expected. Figure 8 also shows that the highest surges occur when the storm crosses the coast from about 070° relative.

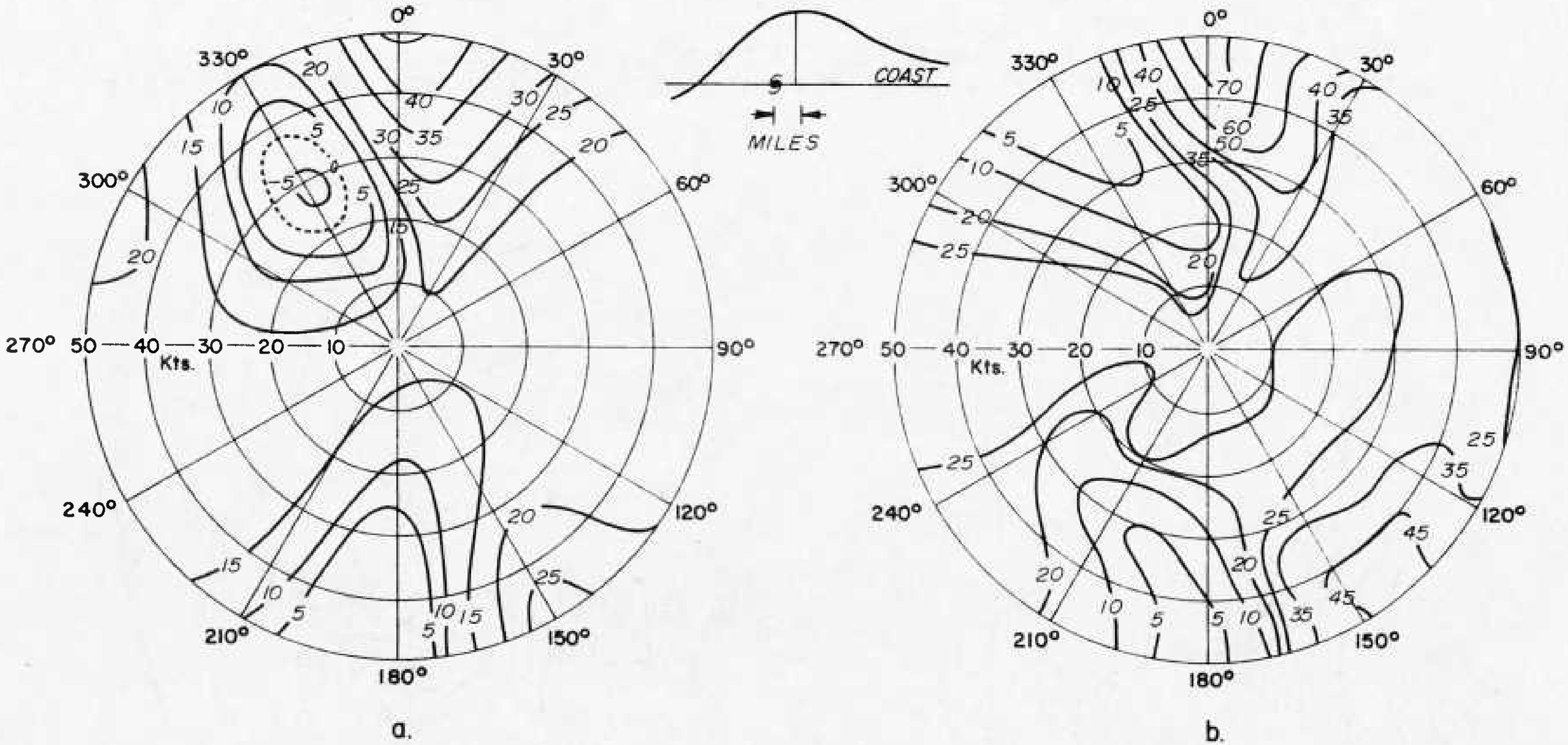


Figure 7. Contours of Distance in Nautical Miles From the Landfall Position to the Point of Peak Surge to the Right Along the Coast, as Observed From Seaward. Radii Are the Storm Speeds in Knots, and Rays Are the Crossing Angles of the Storm to the Coast (varying from 0° for storm motion parallel to the coast with land to the right to 180° for storm motion parallel to the coast with land to the left, and 90° if moving directly ashore). (a) For a Radius of Maximum Wind at 15 Nautical Miles. (b) For a Radius of Maximum Wind at 30 Nautical Miles (after Jelesnianski [44).

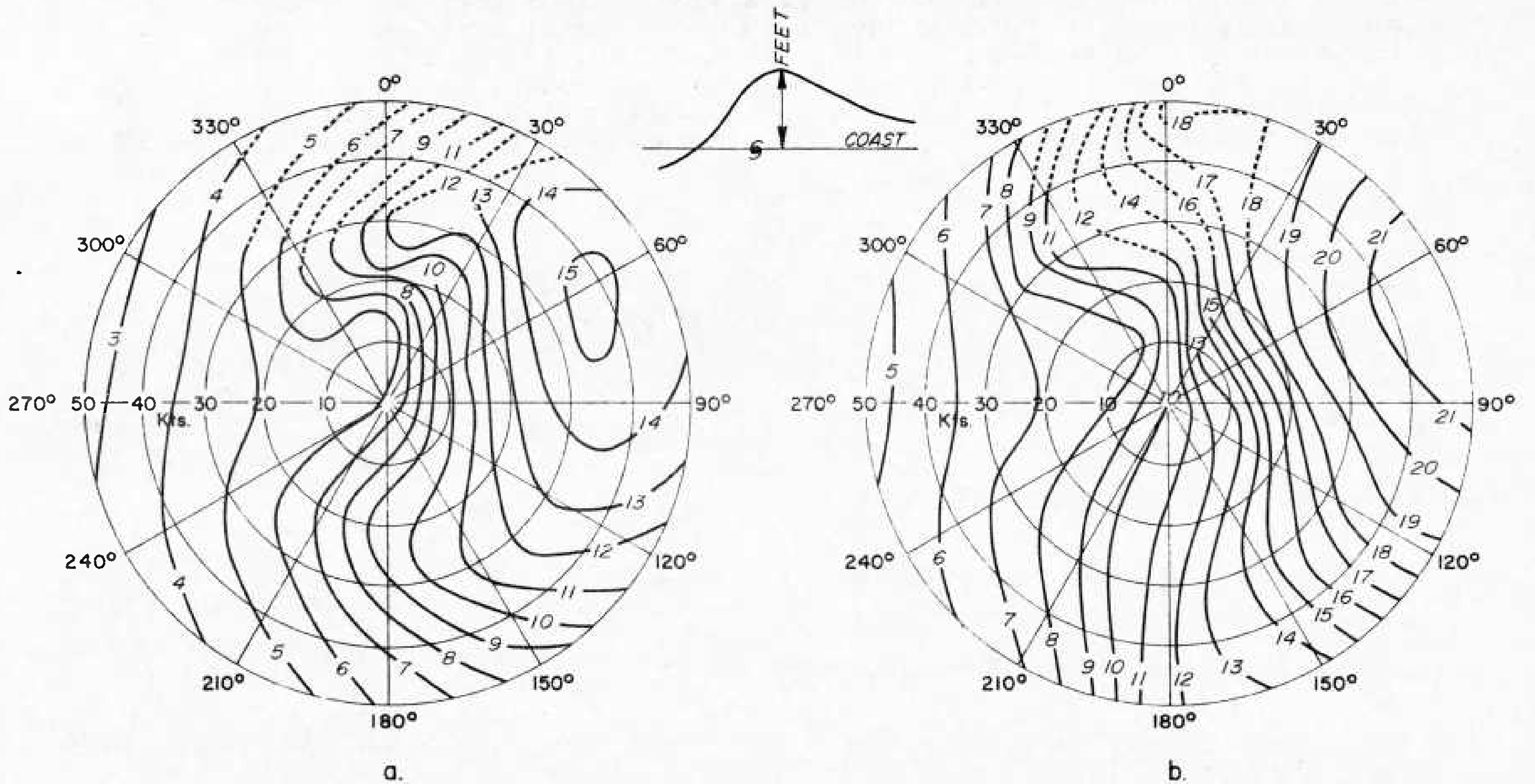


Figure 8. Contours of Peak-Surge Values in Feet for a Standard Storm at the Inner Standard-Basin Boundary. Arguments Are Identical to Figure 7. The Portion of the Figures Where the Height Waves Are Depicted by Broken Lines Directs Attention to the Possibility of Edge-Wave (resurgence) Phenomena That Could be Affecting the Directly Generated Crests With the Indicated Speed and Relative Direction of Storm Movement (after Jelesnianski [44]).

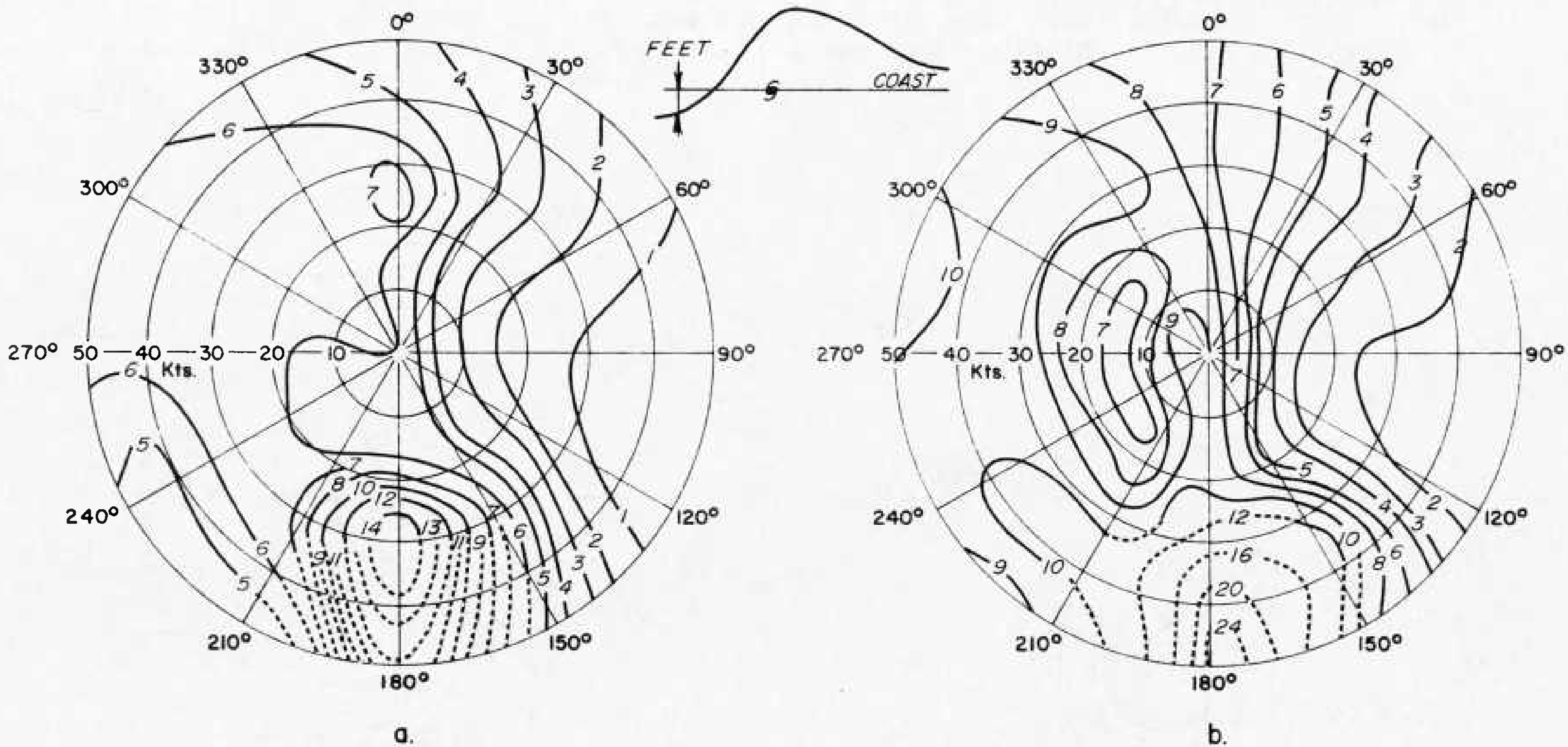


Figure 9. Same as Figure 8 for the Minimum Surge Portrayed at the Time of Peak Surge. The Absolute Minimum Surge Does Not Necessarily Occur at the Time of Peak Surge; Is Transitory and Can Eventually Turn Into Respectable Positive Values After the Passage of the Storm. The Broken Height Curves Again Indicate Storm Motions With Which Edge-Wave (resurgence) Phenomena Are Possible (after Jelesnianski [44]).

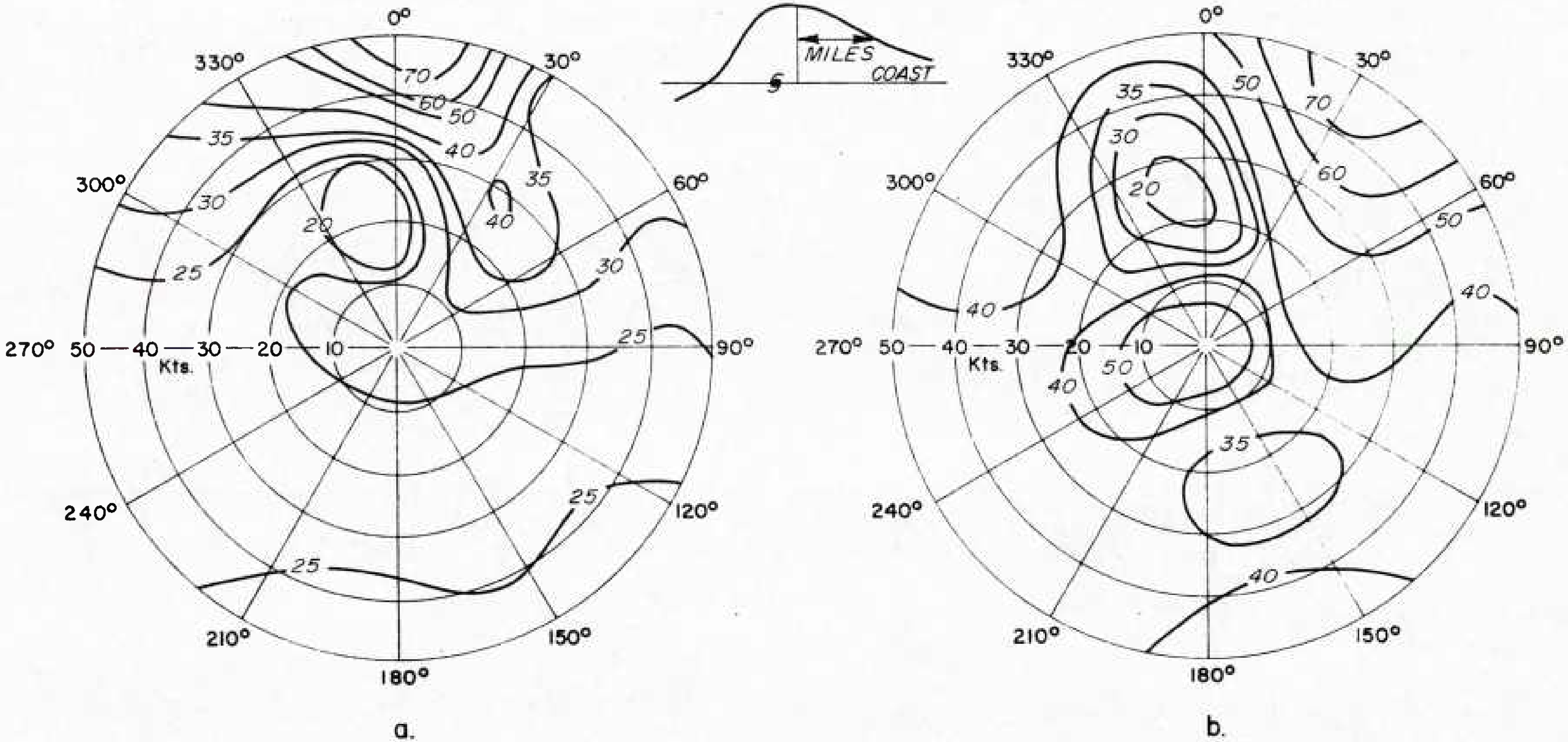


Figure 10. Contours of Distance Along the Inner Standard-Basin Boundary, in Nautical Miles, From the Point of Peak Storm Surge to the Point of 1/2 the Peak-Surge Height to the Right of Landfall (as seen from seaward) (after Jelesnianski [44]).

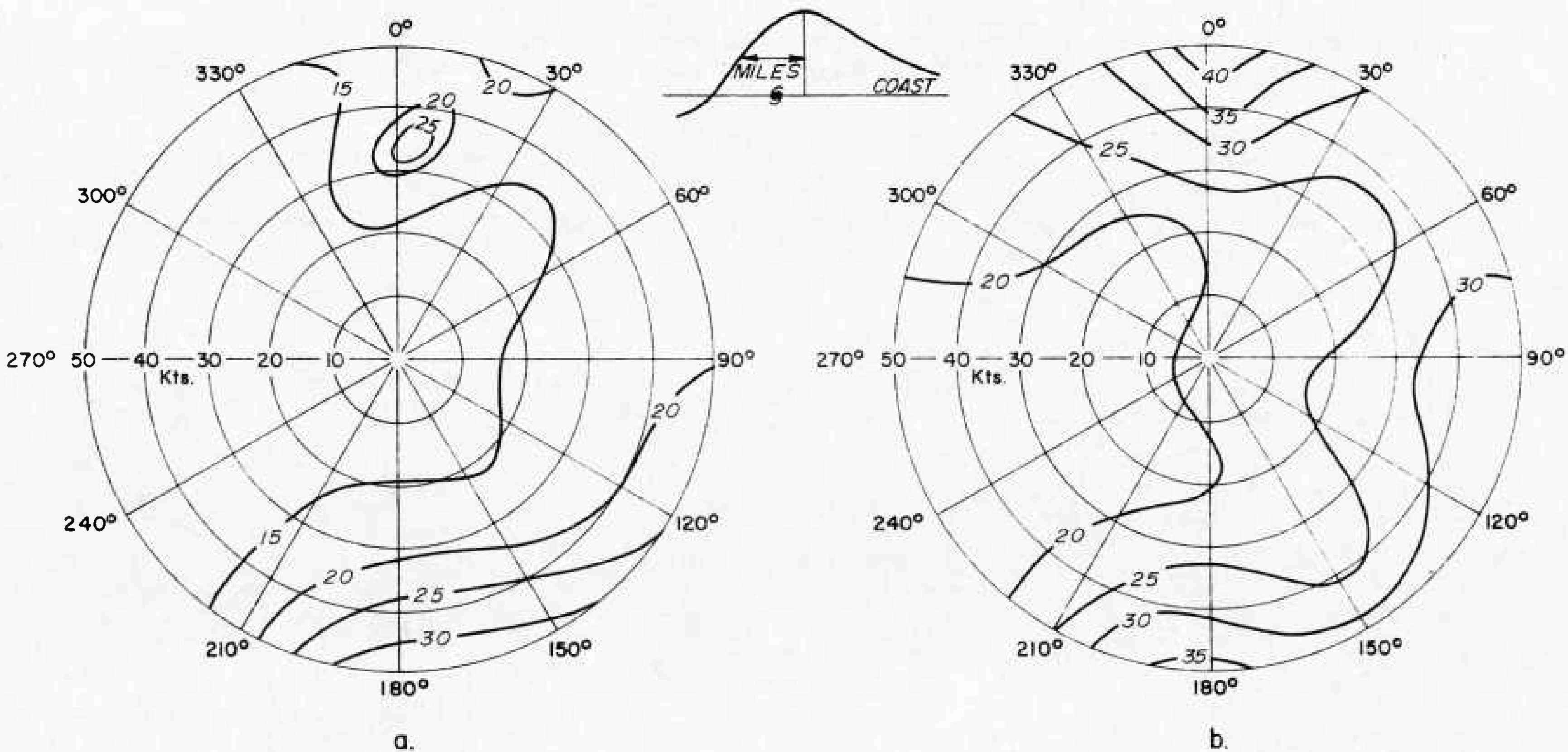


Figure 11. Contours of Distance Along the Inner Standard-Basin Boundary, in Nautical Miles, From the Point of Peak Storm Surge to the Point of 1/2 the Peak-Surge Height to the Left of Landfall (as seen from seaward) (after Jelesnianski [44]).

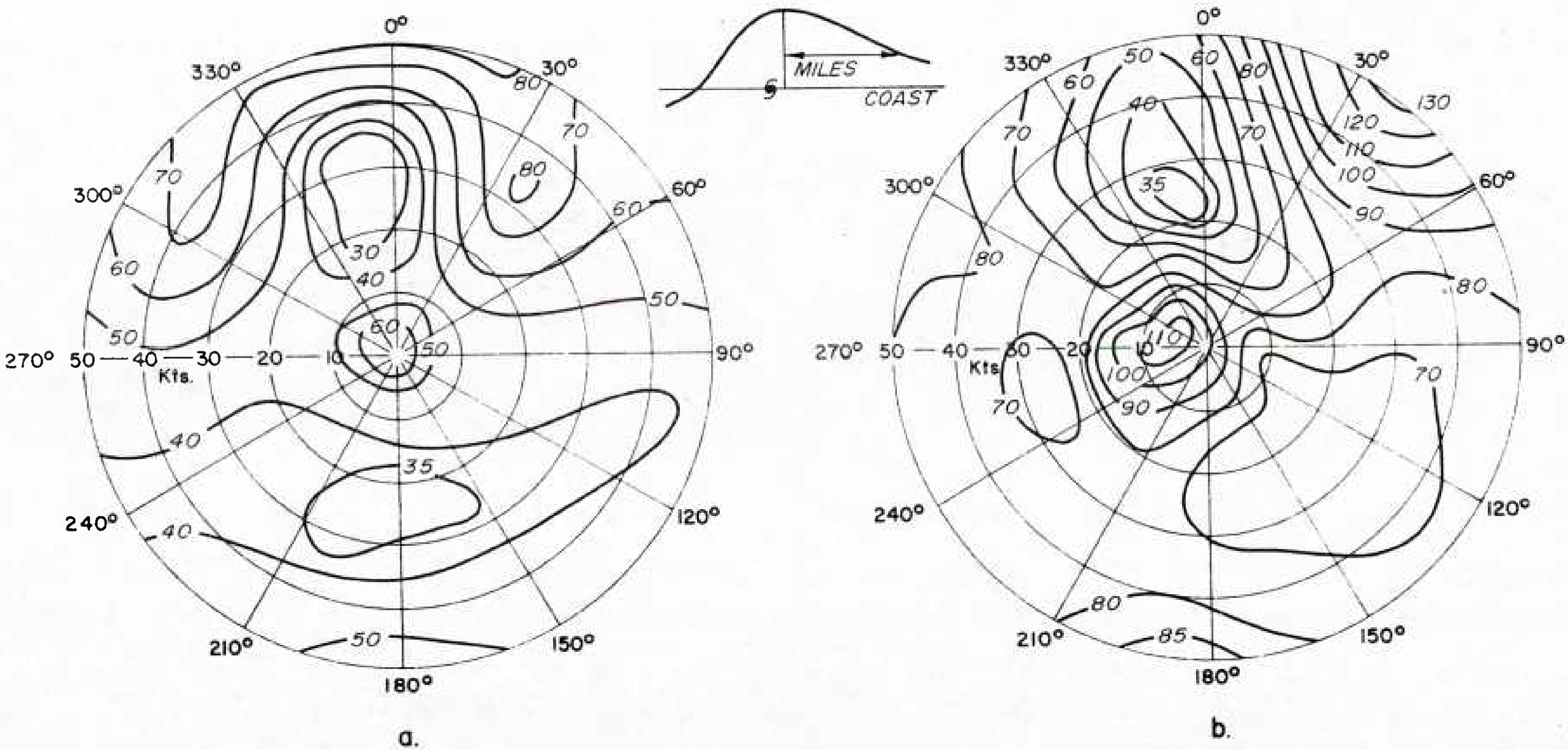


Figure 12. Contours of Distance Along the Inner Standard-Basin Boundary, in Nautical Miles, From the Point of Peak Storm Surge to the Point of 1/4 the Peak-Surge Height (after Jelesnianski [44]).

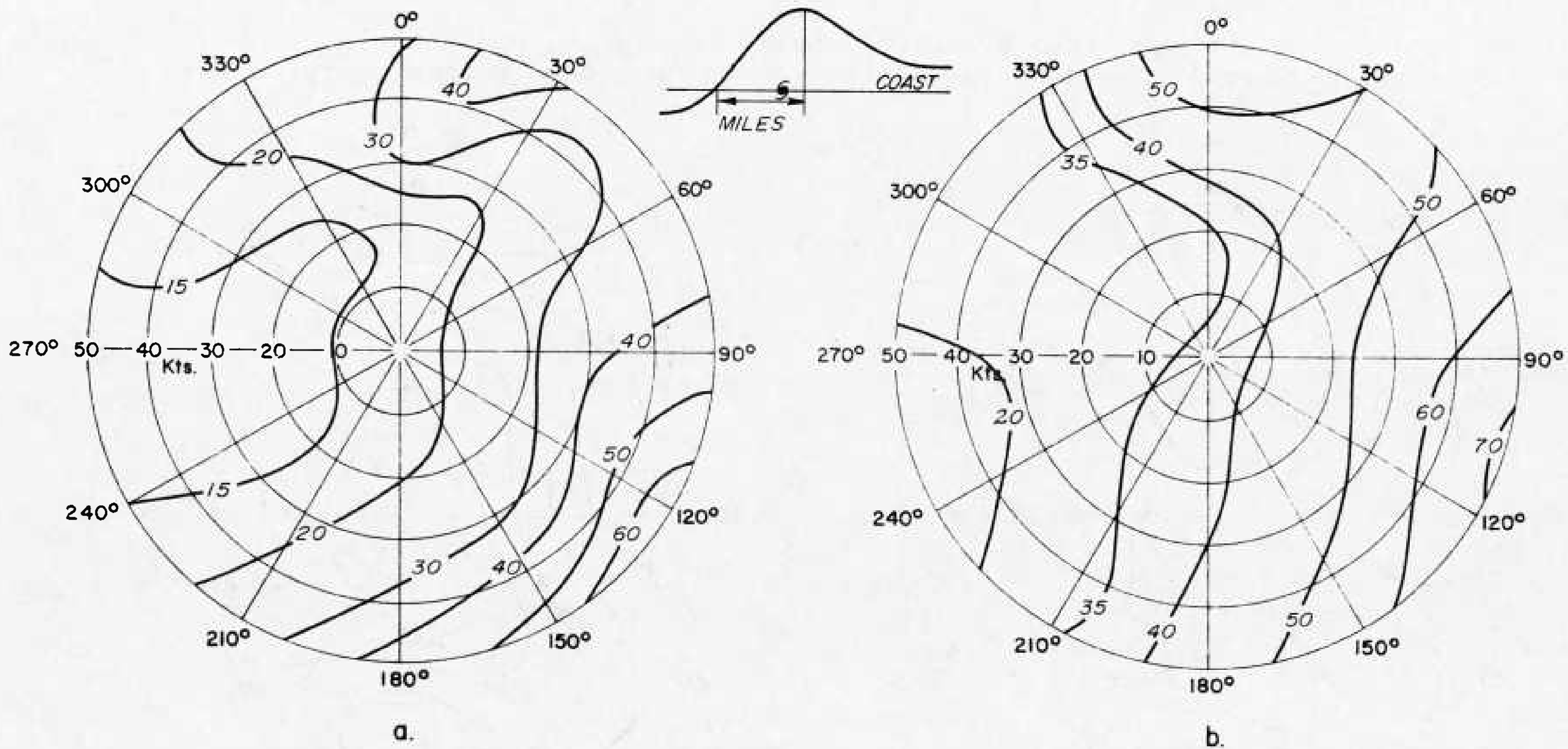


Figure 13. Distance Along the Inner Standard-Basin Boundary Between the Peak Surge and the Zero Surge (after Jelesnianski [44]).

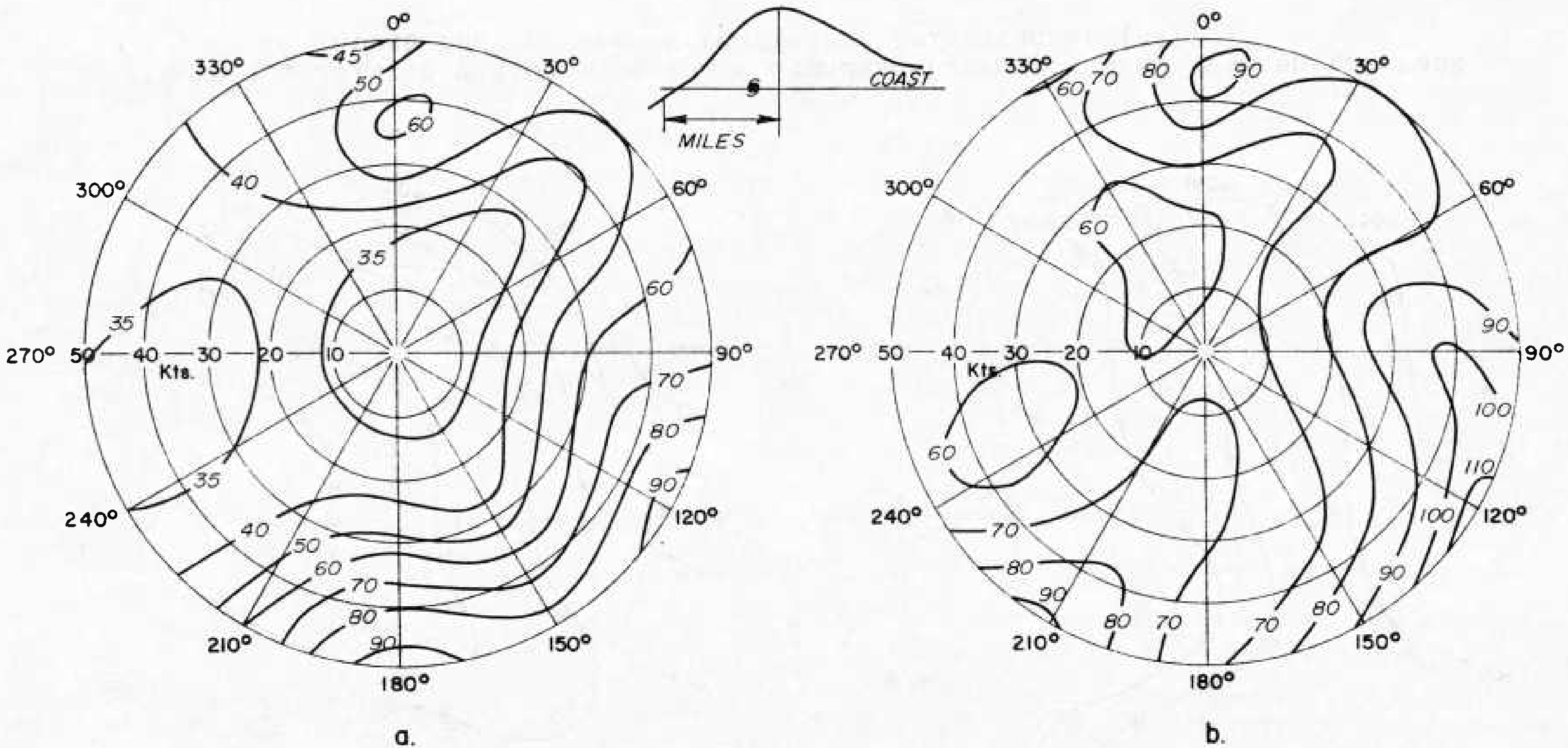


Figure 14. Distance Along the Inner Standard-Basin Boundary Between the Peak Surge and the Minimum Surge (after Jelesnianski [44]).

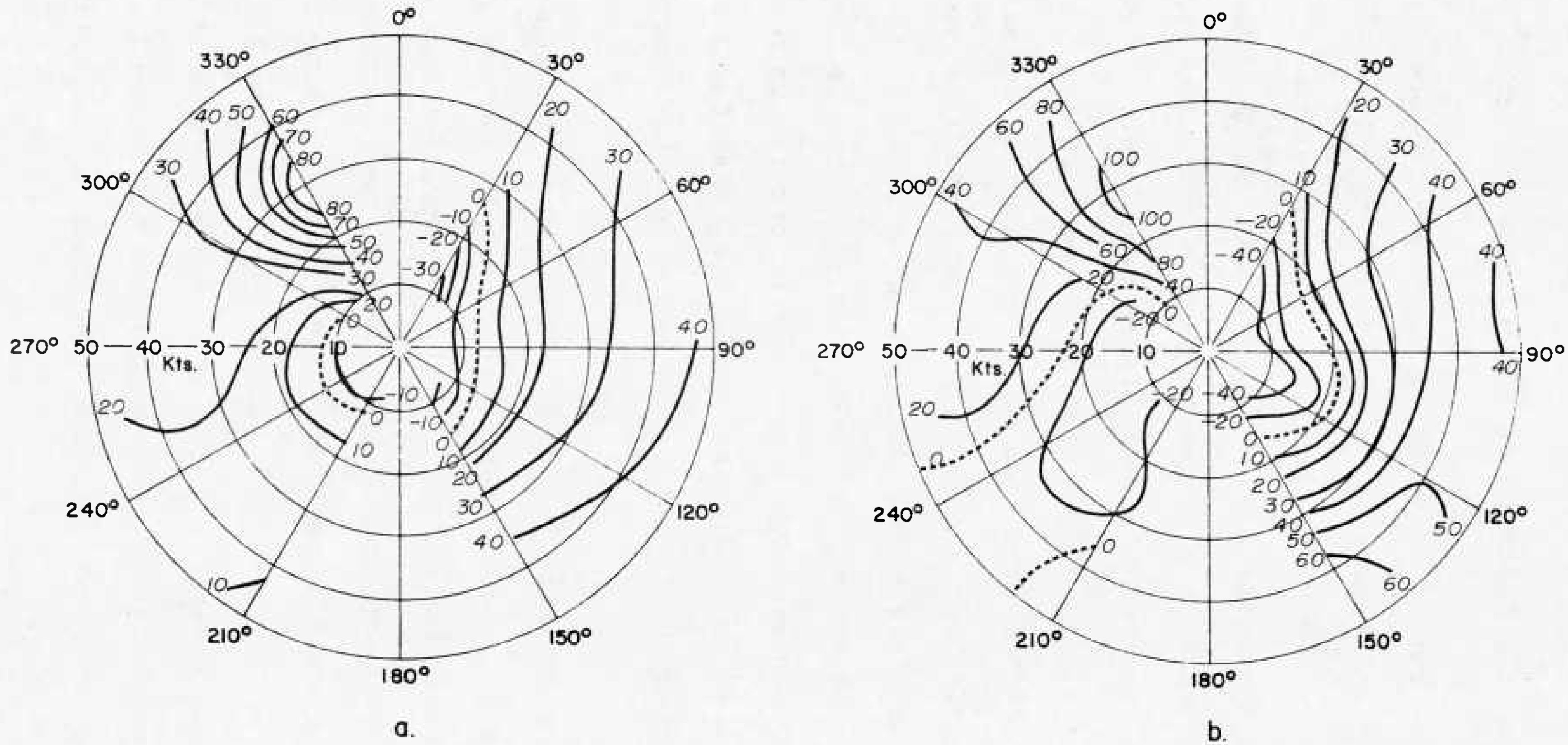


Figure 15. Arrival Time, in Minutes, of Peak Surge at the Inner Standard-Basin Boundary After Landfall. Negative Values Indicate Peak Surge Arrival Before Landfall (after Jelesnianski [44]).

3.2 Correcting the Precomputed Storm Surge for Actual Storms and Basins

Figure 16 provides a solution to the storm-surge relationship between the pressure drop of the storm $\overline{P}$, the Wind Field Correction Factor V_R and the radius of maximum wind R. The arguments are: the Pressure Drop, which is the mean of the sea-level pressure differences along several rays from the center of the storm to the first anticyclonically curved isobars (see fig. 1); and the radius of maximum wind, which is determined either from reconnaissance reports or the weather map. If the maximum winds do not occur as a pronounced peak but in a broad band, the outer edge of this band should be selected. The resultant parameter is the Wind Field Correction Factor V_R, which must be entered into equation (1) in order to modify the precomputed (standard) storm-surge height h_s to obtain the corrected storm-surge height h_c.

The inflow-angle curves depicted in figure 16, represents the crossing angle of the wind relative to the isobars at a distance 87 miles from the center of a standard storm and are intended to provide an indication of cases when the nomogram will produce reasonable results. If the actual inflow angle is considerably different from those given in figure 16, or is erratic, this indicates a change in the structure of the storm is taking place and the nomogram can not be used with the same degree of accuracy until the situation stabilizes.

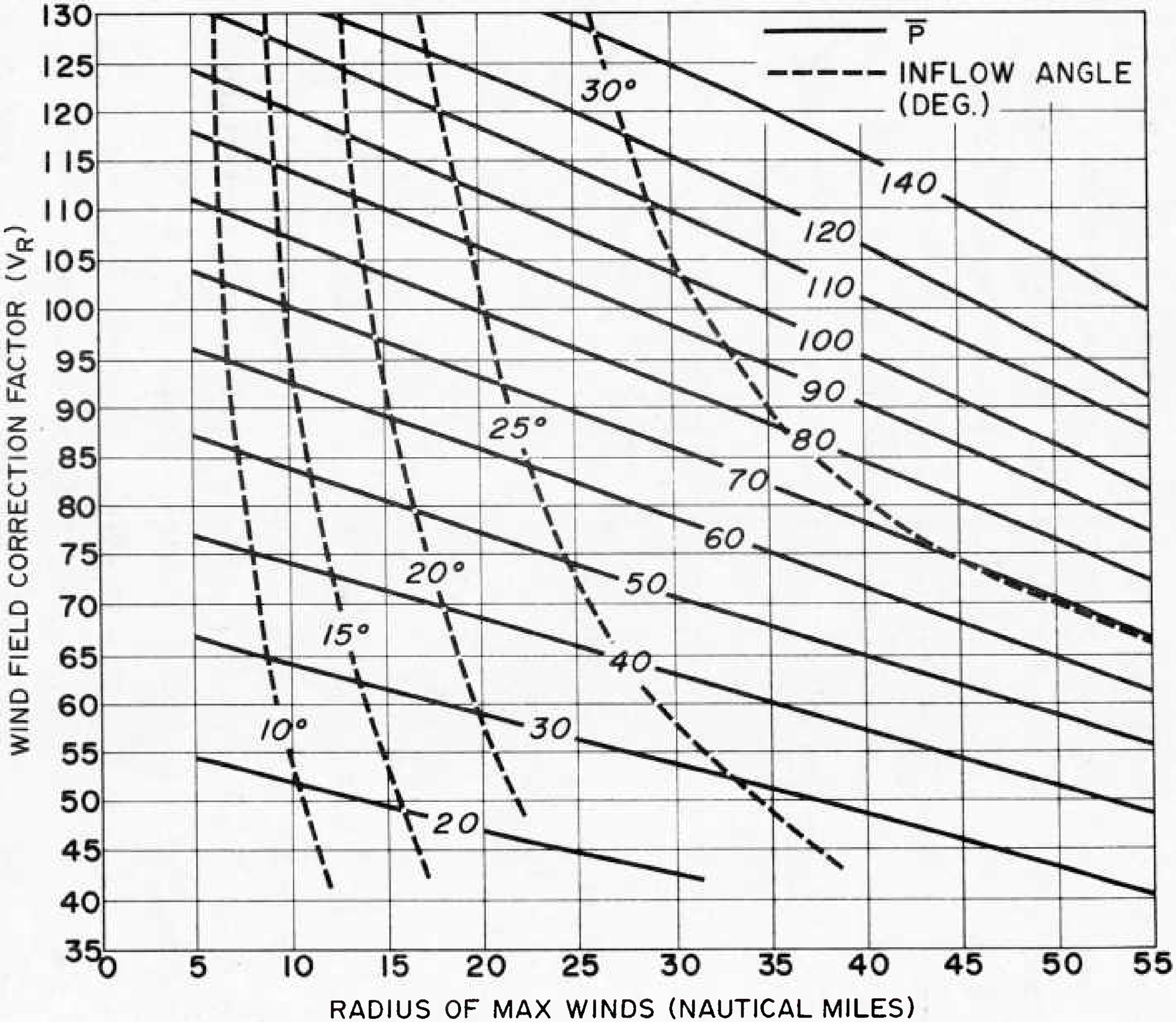


Figure 16. Determination of the Wind Field Correction Factor V_R From the Radius of Maximum Wind in Nautical Miles and Pressure Drop $\overline{P}$. The Inflow Angle Occurs 87 Nautical Miles From Storm Center.

The Depth Profile Corrector Factor F_D is based upon a series of simulations with model storms, and is applied to the precomputed storm-surge profile when the actual depth profile of the basin under consideration varies from that of the standard basin. Figure 17 and 18 provide Depth Profile Correction Factors for selected points along the United States East and Gulf Coasts. Values of F_D for selected points along the Republic of Vietnam coast are provided in appendix D, together with plots of representative depth profiles for the United States Gulf and East Coasts and the RVN coast.

The corrected storm-surge height h_c may now be determined from the following equation:

$$h_c = h_s \left(\frac{V_R}{87}\right)^2 F_D \; ; \qquad (1)$$

where h_s is the precomputed peak storm-surge height obtained from figure 8, V_R is the Wind Field Correction Factor obtained from figure 16 and F_D is the Depth Profile Correction Factor for the basin under consideration. Equation (1) corrects the peak and minimum height; however, all other measurements of the storm-surge profile as deduced from the circular nomograms are unchanged and should be only slightly modified in accordance with the degree of change from h_s to h_c.

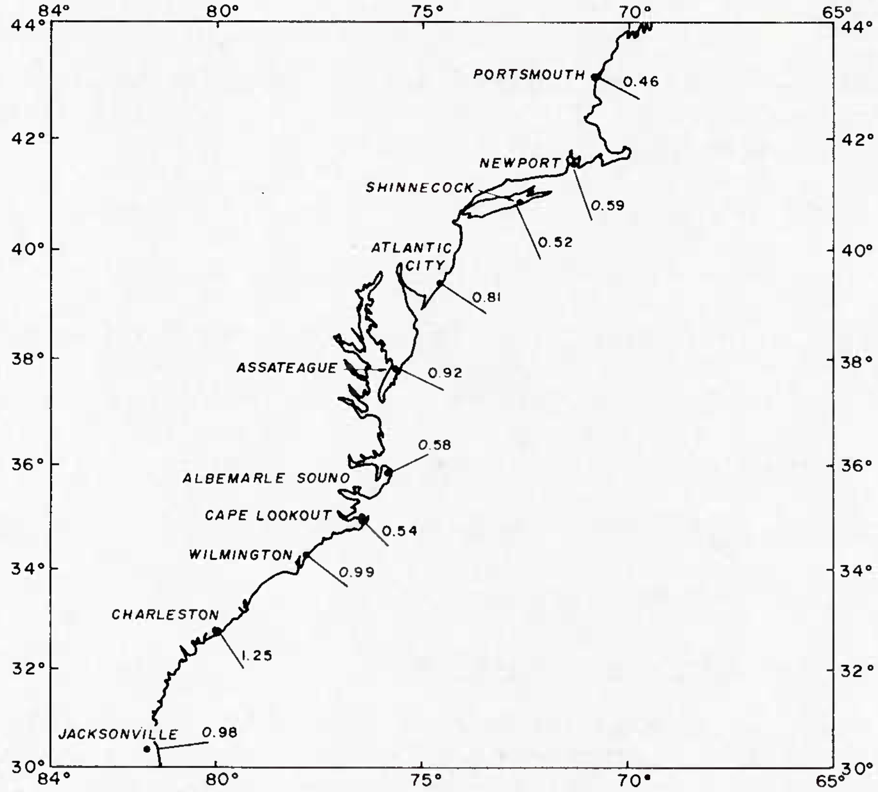


Figure 17. Correction Factors at Selected Points Along the Eastern Seaboard of the United States for Depth Profiles Other Than Standard.

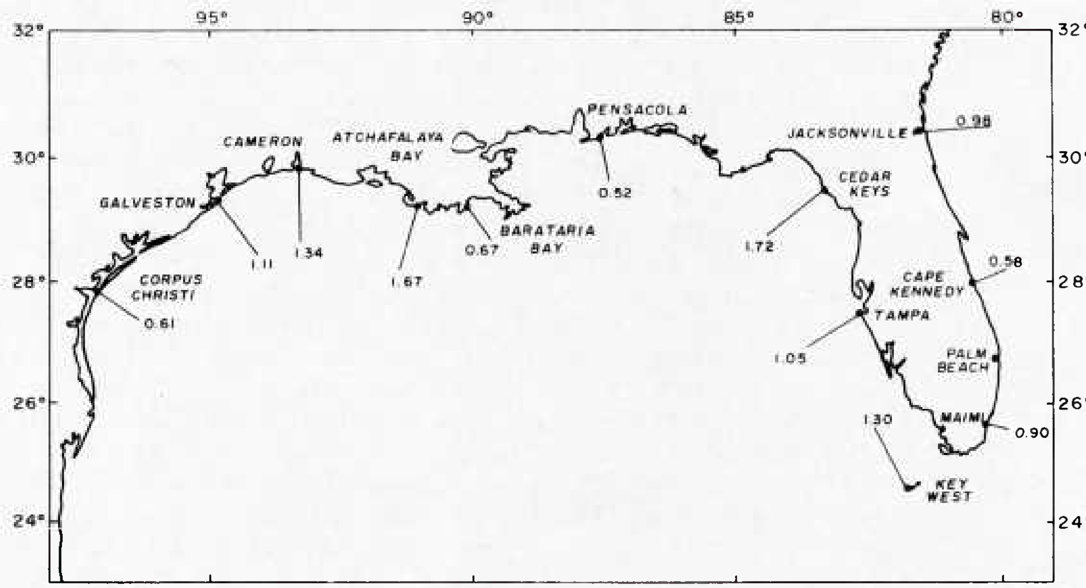


Figure 18. Correction Factors at Selected Points Along the Gulf States and Florida.

3.3 Factors to Be Considered in Projecting Water-Level Forecasts Inland From the Straight, 15-Feet Deep, Inner, Standard-Basin Boundary

After the point of landfall has been forecast and the predicted storm-surge profile has been computed for the 15-feet deep, inner, standard-basin boundary, consideration must subjectively be given to certain inshore environmental factors before the total storm surge or total water level can be forecast. These factors are sea-level anomalies, wind stress, wave set-up, and rain.

(a) Sea-Level Anomalies

A large factor in the total water level will be the astronomical tide. However, a comparison of the records for any tidal observing station will reveal many peaks in actual daily water-level fluctuations that are not explained by the smooth curves that are shown in tide tables. The example presented in figure 19 shows that differences between the predicted and daily mean sea level may exceed a foot for several weeks at a time. There is disagreement as to the cause of these sea-level anomalies. Some believe the variations from predicted heights to be meteorological in nature, while others contend that geophysical factors (celestial influences, basin deformaties, variable water densities and non-uniformity of currents) are primarily involved. These secular variations are not included in published tide tables; because astronomical tides are computed a year or more in advance, and the occurrence and magnitude of many of the anomalies cannot be anticipated. However, those concerned with the prediction of water-level variations -- whether storm surge or merely for purposes of determining tidal effects upon routine navigation, should endeavor to maintain up-to-date knowledge as to the approximate magnitude of the anomaly from a running comparison of tide-gauge depths with the astronomical tide.

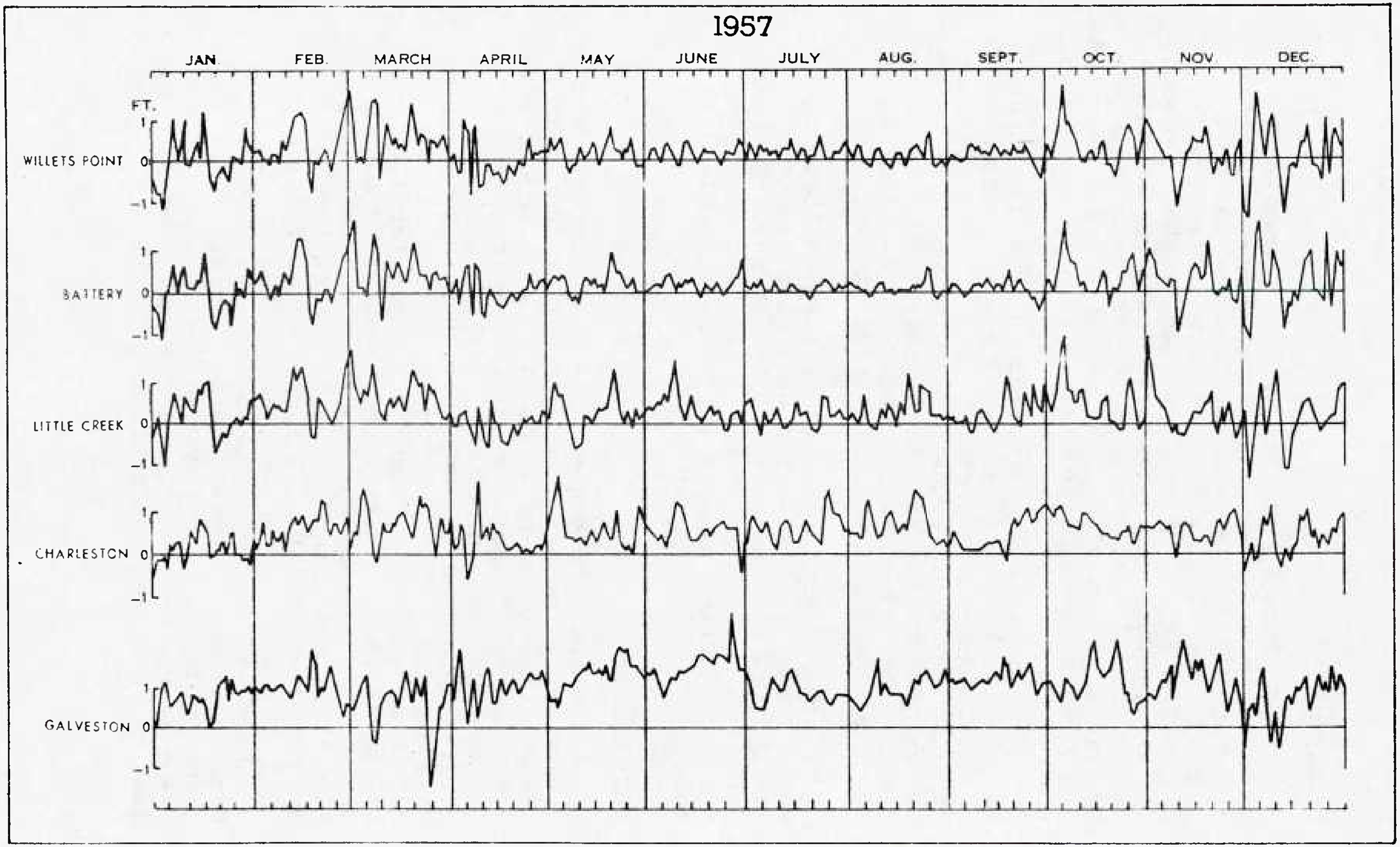


Figure 19. Departures of the Observed Daily Mean-Sea Level From the Predicted Astronomical Tide for Selected Coast and Geodetic Survey Tide Stations, 1957.

(b) Wind Stress

Ekman theory indicates that, in deep water, wind stress on the sea surface causes a mass transport of the near-surface layer in a direction 45° to the right of the wind in the Northern Hemisphere [87], although more recent studies suggest that the angle is usually much less. Nevertheless, as the water becomes shallower, the angle of the mass transport becomes progressively less; and at a depth approaching zero the water moves nearly parallel to the wind.

When the water is constrained by a coastline, the effects on the water level are quite dramatic. A strong wind blowing parallel to a coast with land to the right would cause a mass transport of water toward the coast, raising the water level in that area. This effect is increased if the wind has a onshore component, as shown in figure 20.

As the water depth becomes very shallow, the water tends to move in the same direction as the wind. This becomes quite important when the storm surge has raised the water level above the berm, dunes or barrier islands and the coastal land is relatively flat, as shown in figure 21.

(c) Wave Set-Up

Waves that steepen and break as surf may run up the slope of the beach to a height greater than the crest of the breaking wave. If the waves are frequent and large, as in a hurricane, the water in the up-rush (run-up) of the breaking wave does not fully return to surf-zone level before the next wave arrives. This continual addition of more water, called wave set-up, causes the water level to increase inside the surf zone, as shown in figure 22. The water run-up or up-rush zone, though transitory in nature, may extend the inner water line to an even greater height on the shore (see fig. 22).

Wave set-up that tops the coastal dunes or barrier island can pave the way for extensive inland flooding. Once flooding has established a means of ingress, the waves and surf zone move inland as indicated in figure 23.

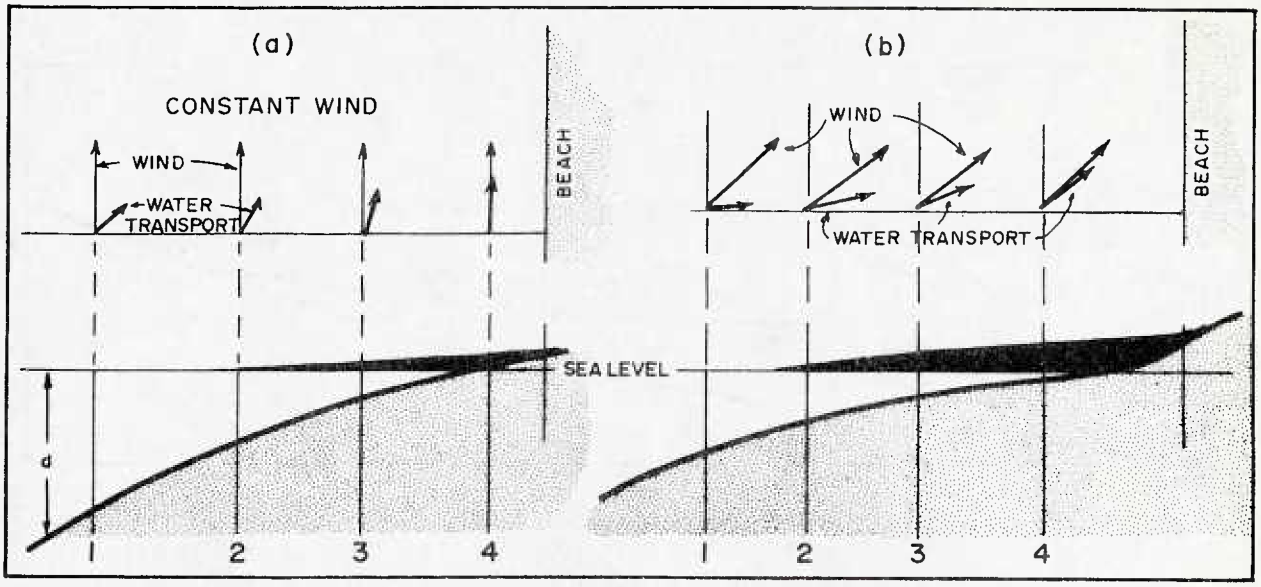


Figure 20. The Effect of Wind Stress Upon Inshore Waters. (a) As the Water Depth Decreases, the Water Movement Becomes More Nearly Parallel to the Wind and Increases in Speed. There Would Probably Be a Strong Littoral (near-the-shore) Current Between Points 3 and 4. (b) If the Wind Direction Is More Onshore, the Shallow Water (near-parallel) Wind Stress Causes a Greater Accumulation of Water on the Beach.

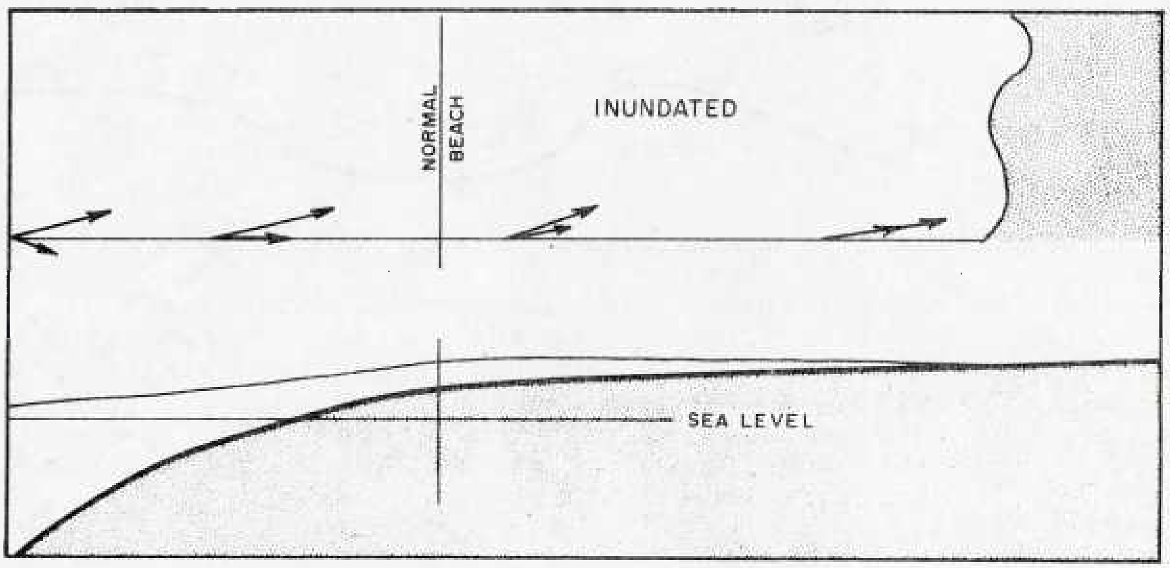


Figure 21. Extensive Flooding Can Occur From Wind Stress if the Water Level Tops the Dunes and the Back Shore Is Moderately Flat. Wind Stress on Shallow Water Causes the Water Motion to Approach That of the Wind Direction.

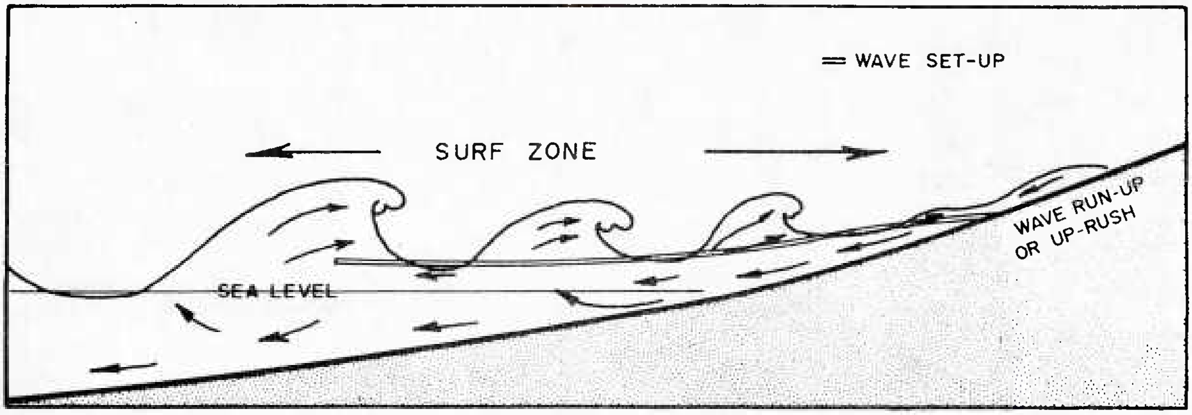


Figure 22. With Mountainous Waves and Surf, as Generated by a Mature Tropical Cyclone, the Incoming Water in the Surf Zone Is in Excess of That Which Can Drain Back by Gravity. This Excess of Water Is Called Wave Set-Up.

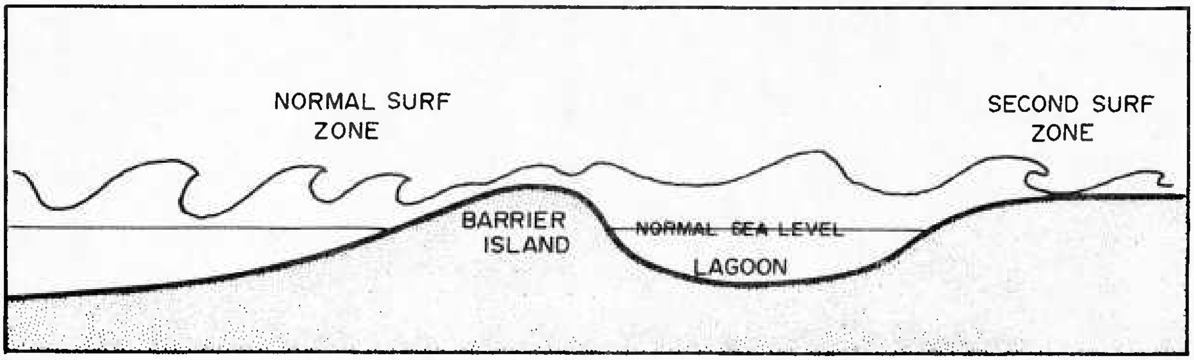


Figure 23. Barrier Islands Can Also Act as a Barrier to Water Flowing Back to the Ocean. In This Situation the Wave Set-Up Has Topped the Barrier Island and Flooded the Lagoon, Allowing Extensive Inshore Flooding. If the Lagoon Is Shallow, a Continuous Surf Zone May Develop From the Ocean Surf Zone Inland.

(d) Rain

The storm surge is the phenomenon which is the primary cause of damage produced by tropical cyclones which cross or closely approach a coastline. Due consideration must also be given, however, to the amount of rain that will fall in and upslope from the forecast coastal area. If the rain is heavy enough and commences sufficiently far in advance of the storm surge, as with a slow-moving storm, flooding from the rain may make a significant contribution to the total water level. River deltas and flat coastal plains with poor drainage are particularly susceptible to the effect of flooding originating from prolonged heavy rainfall farther inland. It can literally be a back-door surge. This is discussed in appendix A and illustrated in figure A-6.

3.4 Some Thumb Rules to Aid in Storm-Surge Forecasting

The Storm

(1) The pressure drop across the storm may sometimes be difficult to determine because of isobar shape. If in doubt, use the normal or average pressure for that area before the storm arrived as the outer pressure.

(2) To determine the central pressure of a well-developed tropical cyclone, if there are only extrapolated isobars from which to work, reduce the pressure at the rate of 1 millibar per mile for the last 30 miles to the center of the storm.

(3) To determine the central pressure of extra-tropical cyclones from the isobars of a surface chart, continue the gradient of the inner 100 miles to the center.

(4) If the maximum wind is determined to be a band of some width, use the outer radius as the radius of maximum wind R. In the few occasions where this occurs, it will have the effect of broadening the peak-surge area.

(5) When storms are larger than the model storm (with the 35-knot wind radius extending out beyond a distance of 87 nautical miles from the center - figure 3), the storm surge will extend to a greater distance along the coast. The 35-knot wind radius and the 1/4 of the height of the peak surge seem to coincide. Adjust the surge profile accordingly.

(6) The sea level rises 1 foot for each pressure drop of 30 millibars. This relation cannot be used directly, because of complex fluid dynamic effects; but pressure effects are used in the derivation of the nomograms.

F_D, Depth Profile Correction Factor

(1) If the storm-surge profile extends into an area with a different depth-correction factor, rework the storm-surge correction equation for that portion of the coast using the new F_D, correcting the storm-surge profile so that it

is correctly drawn for each area. The two profile curves should be smoothed to present a single corrected profile.

Wind-Stress Corrections

Wind stress depends on the wind speed, air density, and roughness of the water surface. In deep water this surface force causes a current to flow at an acute angle to the right of the wind in the Northern Hemisphere; but as the water depth decreases, the current becomes more in line with the wind.

(1) A wind parallel to a straight coast with land to the right will raise the water level slightly along the coast and can create strong littoral currents.

(2) As the wind becomes more onshore the water level increases as the wind speed increases, with higher water levels resulting where the beach becomes concave or where there is channelling and funnelling into bays, river mouths, and inlets.

(3) At hurricane wind speeds, comparisons of the storm-surge high-water marks along the beach with a storm-surge hindcast for the inner standard-basin boundary indicates that wind stress and wave set-up contribute 1 to 3 feet of additional water height between the inner standard-basin boundary and the beach.

Wave Set-Up and Wave Run-Up

Wave set-up is the increase of water height in the surf zone caused by breaking waves bringing more water to the inner surf zone and beach than is being removed. Wave run-up, also called up-rush, is a transitory condition of water running up the slope of the beach as the

result of a wave breaking. Most of the water normally runs back to a previous level before the next wave breaks.

(1) Wave set-up starts at moderate wind speeds and increases to 1 to 3 feet at hurricane wind speed, depending upon beach slope, surf-zone dimensions and wave direction relative to the beach.

(2) Wave run-up varies with the slope of the beach, wave direction, wave height and type of breaker. The run-up averages approximately the significant (1/3 highest) breaker height, but with wide variations caused by wave diffraction and refraction.

Shoreline and Back-Shore Considerations

(1) Barrier islands, levees, sea walls, etc., if topped by a surge, may act to prevent the water from flowing back to the sea.

(2) Water in a lake or bay in the lee of a barrier to a surge will be below normal from wind stress. With hurricane-speed winds, water slope due to wind stress in the lake or enclosed bay may be as much as 1 foot per 2 to 4 miles.

(3) Long estuaries, bays and bayous that have converging shorelines and decreasing depths may experience surges as much as double the surge at the coast, because of the combined effects of convergence, wind stress, wave refraction and wave set-up.

(4) Bays and bodies of water open to the sea and in line with a wind of hurricane force which is blowing offshore may have negative surges of several feet, if there is some bottom restriction at the mouth to prevent offsetting deep water from flowing back into the bay.

Variables and Verification

(1) Holliday [35] points out that the center of a hurricane may oscillate continuously over a small area, making a precision forecast of the landfall point difficult even with the storm under continuous radar surveillance.

(2) Harris [27] found that the average distance from the storm track to the peak reported surge was 20 miles, with 2/3 of the cases falling between 5 miles on the left and 35 miles on the right. Extreme cases were 20 miles on the left and 100 miles on the right.

(3) High-water marks are affected by small-scale dynamic processes, and may vary as much as 2 to 3 feet within distances of a few miles.

BIBLIOGRAPHY AND REFERENCES

1. ARMSTRONG, JOHN, B., "Effect of Meteorolcgical Conditions on Sea Level." Canada, Meteorological Branch, CIR-3747; TEC-429, 1962.

2. BHASKARA RAO, N. S. and S. MAZUMDAR, "Technique for Forecasting Storm Waves." Indian Journal of Meteorology and Geophysics, Delhi, 17(3):333-346, 1966.

3. BODINE, B. R., "Hurricane Surge Frequency Estimated for the Gulf Coast of Texas." U.S. Coastal Engineering Research Center, Washington, D. C., Tech. Memo. No. 26, 32 p., 1969.

4. BRETSCHNEIDER, C. L., "Engineering Aspects of Hurricane Surge." Proc., Tech. Conf. on Hurricanes, Amer. Met. Soc., Miami Beach, Florida, 1958.

5. ____________, B. J. FE MEHAUTE and LOUIS ALLEN, "Oceanographic, Meteorological, and Coastal Engineering Evaluation of the March 1962 East Coast Storms Along the South Bethnay, Delaware Coast Area." National Engineering Science Co., Tech. Rpt., SN-96, 1963.

6. ____________, and J. I. COLLINS, "Winds, Waves, Tides, and Wave Run-up at Ventnor, New Jersey, During the Storm of March 5-8, 1962." National Engineering Science Co., Tech. Rpt., SN-138, 1963.

7. ____________, "Prediction of Hurricane Surge, an Investigation for Corpus Christi, Texas, and Vicinity." National Engineering Co., Tech. Rpt. Contract No. DA-41-243-CIVENG-63-69, 1963.

8. ____________, "The Ash Wednesday East Coast Storm March 5-8, 1962, A Hindcase of Events, Causes and Effects." National Engineering Science Co., Tech. Rpt., SN-134-4, 1964.

9. ____________, "Storm Surges." Advances in Hydroscience, N.Y., Vol. 4, pp. 341-418, 1967.

10. ____________, "Fundamentals of Ocean Engineering, PT. 5, Calculating Storm Surge Criteria for the Continental Shelf." Ocean Industry, Houston, Texas, 2(12):42-47, 1967.

11. ____________, "Fundamentals of Ocean Engineering, PT. 6, Estimating Storm Surges Over the Continental Shelf." Ocean Industry, Houston, Texas, 3(1):46-47, 1968.

12. ____________, and G. S. PICK, "Bibliography on Storm Surges and Related Subjects." National Engineering Science Co., Pasadena, Calif., 48 p., 1968.

13. CARR, JOHN T., JR., "Hurricanes Affecting the Texas Gulf Coast." Texas Water Development Board, Rpt. No. 49, 58 p., 1967.

14. CHASE, J., "A Comparison of Certain North Atlantic Wind, Tide Gauge and Current Data." J. Mar. Res., 13(1):22-31, 1954.

15. COOPERMAN, A. I. and H. E. ROSENDALL, "Great Atlantic Coast Storm, 1962." Mariners Weather Log, 6(3):79-85, U.S. Weather Bureau, 1962.

16. DEFANT, A., "Physical Oceanography." Vols. I and II, Pergamon Press, 1961.

17. DONN, W. L., "An Empirical Basis for Forecasting Storm Tides." Bul. Amer. Met. Soc., Vol. 39 (12), pp. 640-647, 1958.

18. FREEMAN, J. C., JR., L. BAER and G. H. JUNG, "The Bathystrophic Storm Tide." J. Mar. Rsch., Vol. 16(1), pp. 12-22, 1957.

19. GAUL, R. D. and H. B. STEWARD, "Nearshore Ocean Currents Off San Diego, California." J. Geophys. Res., 65(5), pp. 1543-1556, 1960.

20. GOUDEAU, D. A. and W. C. CONNER, "Storm Surge Over the Mississippi River Delta Accompanying Hurricane BETSY, 1965." Monthly Weather Review, Washington, D. C., 96(2):118-124, 1968.

21. GRAHAM, H. E. and D. E. NUNN, "Meteorological Considerations Pertinent to Standard Project Hurricane, Altantic and Gulf Coasts of the United States." Natl. Hurr. Rsch. Proj. Rpt. No. 33, U.S. Weather Bureau, 1959.

22. ____________ and G. N. HUDSON, "Surface Wind Near the Center of Hurricanes (and Other Cyclones)." Natl. Hurr. Rsch. Proj. Rpt. No. 39, U.S. Weather Bureau, Washington, D. C. 200 p., 1960.

23. GREENSPAN, H. P., "The Generation of Edge Waves by Moving Pressure Distributions." Journal of Fluid-Mechanics, Vol. 1, No. 6, pp. 574-592, 1956.

24. GROEN, P., "Methods for Estimating Dynamic Slopes and Currents in Shallow Water." J. Mar. Rsch., 7(3), pp. 313-316, 1948.

25. GROVES, GORDON W., "Day to Day Variation of Sea Level." Met. Monograms, Amer. Met. Soc., 2(10), pp. 32-45, 1957.

26. HAGUE, JOHN D., "An Investigation of Practical Hurricane Forecasting." U.S. Naval Postgraduate School, Monterey, Calif., 59 p., 1960.

27. HARRIS, D. LEE, "Some Problems Involved in the Study of Storm Surges." Natl. Hurr. Rsch. Proj. Rpt. No. 4, U.S. Weather Bureau, 33 pp., 1956.

28. ____________, "Hurricane AUDREY Storm Tide." Natl. Hurr. Rsch. Proj. Rpt. No. 23, U.S. Weather Bureau, 19 pp., 1958.

29. ____________, "An Interim Hurricane Storm Surge Forecasting Guide." Natl. Hurr. Rsch. Proj. Rpt. No. 32, U.S. Weather Bureau, 24 pp., 1959.

30. ____________, "Characteristics of the Hurricane Storm Surge." U.S. Weather Bureau Tech. Paper No. 48, 1963.

31. ____________ and ALDO ANGELO, "Regression Model for Storm Surge Prediction." Monthly Weather Review, Washington, D. C., 91(10/12):710-726, 1963.

32. ____________ and EUGENE W. HOOVER, "Pronosticando Marejadas Fuertes Inducidas Por Huracanes [Forecasting Hurricane-Induced High Water Surges]." Geofisica Internacional, Mexico City, 4(2/4):63-76, April/Dec. 1964 (received 1966).

33. ____________, "Hurricane Storm Surges." (In: Proc., Hurricane Symposium, Society for Oceanography, Houston, Texas, Oct. 1966. Ed. by Sidney A. Stubbs), pp. 200-228, 1967.

34. HIDAKA, K., "Dynamics of Ocean Currents Parallel to a Long Straight Coast." Geophys. Mag. (Tokyo), 28, pp. 357-365, 1958.

35. HOLLIDAY, CHARLES R., "A Comparison of Hurricane Center Fixes Made by Land Bases, Radar and Reconnaissance Aircraft." ESSA, Weather Bureau, Tech. Note 31-RADAR-1, 1966.

36. HOOVER, R. A., "Empirical Relationships of the Central Pressures in Hurricanes to the Maximum Surge and Storm Tide." Monthly Weather Review, 85(5), pp. 167-174, 1957.

37. HUBERT, W. E., R. C. SCHLUSSER and T. LAEVASTU, "The Responses of the Ocean to the Action of Atmospheric Forces and Accounting of These Responses in U.S. Fleet Numerical Weather Facility's Oceanographic Analyses and Forecasting Program." Fleet Numerical Weather Facility, Tech. Note No. 12, 1965.

38. ____________ and T. LAEVASTU, "Synoptic Analysis and Forecasting of Surface Currents." Navy Weather Research Facility NWRF 36-0667-127, 1967.

39. HUNKINS, KENNETH L., "Tides and Storm Surge Observations in the Chukchi Sea." Limnology and Oceanography, Lawrence, Kansas, 10(1):29-39, 1965.

40. ICHIYE, T., "The Response of a Stratified, Bounded Ocean to Variable Wind Stresses." Oceanog. Mag. 10, pp. 19-63, 1958.

41. JAPAN METEOROLOGICAL AGENCY, "Numerical Investigation of Storm Surges in Ariake Bay." Tech. Rpt. No. 28, March 1968.

42. JELESNIANSKI, C. P., "A Numerical Computation of Storm Tides by a Tropical Storm Impinging on a Continental Shelf." Monthly Weather Review, 93(6), pp. 343-358, 1965.

43. ____________, "Numerical Computations of Storm Surges Without Bottom Stress." Monthly Weather Review, 94(6), pp. 379-394, 1966.

44. ____________, "Numerical Computations of Storm Surges With Bottom Stress." Monthly Weather Review, 95(1), pp. 740-756, 1967.

45. JENSEN, HANS ERIK and STEEN WEYWADT, "Forecasting of Storm Surges in the North Sea, PT. 1." Copenhagen, Institute of Mathematical Statistics and Operations Research, Tech. Univ. of Denmark, 62 p., 1966.

46. ____________, "Forecasting of Storm Surges in the North Sea, Pt. 2." Copenhagen, Institute of Mathematical Statistics and Operations Research, Tech. Univ. of Denmark, 75 p., 1968.

47. JOHNSON, EDWARD P., "Example of Radar as a Tool in Forecasting Tidal Flooding." U.S. Weather Bureau, Eastern Region Tech. Memorandum WBTMER-24, 7 p., 1967.

48. KEERS, J. F., "The Meteorological Conditions Leading to Storm Surges in the North Sea." Meteorological Magazine, London, 95(1130):261-272, September 1966.

49. KAJIURA, K., "A Theoretical and Empirical Study of Storm Induced Water Level Anomalies." Texas A&M University, Dept. of Oceanography and Meteorology, A&M Project 202, Ref. 59-23F, 1959.

50. LAMB, H., "Hydrodynamics." 6th ed., Cambridge Univ. Press, England, 738 pp., 1932.

51. LAWFORD, A. L., "Change in the Relationship Between Wind and Surface Water Movement at Higher Wind Speeds." Trans Amer. Geophys. Un. 37(6), pp. 691-693, 1956.

52. LENNON, G. W., "Identification of Weather Conditions Associated With the Generation of Major Storm Surges Along the West Coast of the British Isles." Royal Met. Soc., Qtr. J., 89(381):381-394, 1963.

53. LONGUET-HIGGINS, M. S., "Mass Transport in Water Waves." Phil. Trans. Royal Soc. London Ser. A. Moth. Phys. Sci. 245(905), pp. 535-681, 1953.

54. ____________ and R. W. STEWARD, "A Note on Wave Set-Up." J. Mar. Rsch., Vol. 21, No. 1, pp. 4-10, 1963.

55. MANDELBAUM, H., "Evidence for a Critical Wind Velocity for Air-Sea Boundary Processes." Trans Amer. Geophys. Un., 37(6), pp. 685-690, 1956.

56. MILLER, A. R., "The Effect of Steady Winds on Sea Level at Atlantic City." Met. Monographs, Amer. Met. Soc., 2(10), pp. 24-31, 1957.

57. ____________, "The Effects of Winds on Water Levels on the New England Coast." Limnol. and Oceanogr. 3(1), pp. 1-14, 1958.

58. MIYAZAKI, M., "Averaged Wind-Stress Relation on the Sea Surface." Oceanogr. Mag., Tokyo, 3(2), pp. 75-77, 1951.

59. ___________, "Numerical Computation of the Storm Surge of Hurricane CARLA 1961 in the Gulf of Mexico." Oceanogr. Mag., Tokyo, 17(1/2):109-140, 1965.

60. MUNK, W., F. SNODGRASS and G. CARRIER, "Edge Waves on the Continental Shelf." Science, Vol. 123, pp. 127-132, 1956.

61. NOMITSU, T., "A Theory of the Rising Stage of Drift Current in the Ocean: I. The Case of No Bottom Current." Memoirs, College of Science, Kyoto Imperial Univ. (Series A), Vol. 16, pp. 160-175, 1933.

62. ___________, "On the Development of the Slope Current and the Barometric Current in the Ocean: I. The Case of No Bottom-Current." Memoirs, College of Science, Kyoto Imperial Univ. (Series A), Vol. 16, pp. 203-241, 1933.

63. ___________, "A Theory of the Rising Stage of Drift Current in the Ocean: III. The Case of a Finite Bottom-Friction Depending on the Slip Velocity." Memoirs, College of Science, Kyoto Imperial Univ. (Series A), Vol. 16, pp. 309-331, 1933.

64. ___________, "Coast Effect Upon the Ocean Current and the Sea Level: II. Changing State." Memoirs, College of Science, Kyoto Imperial Univ. (Series A), Vol. 16, pp. 249-280, 1934.

65. ___________ and T. TAKEGAMI, "On the Development of the Slope Current and the Barometric Current in the Ocean: II. Different Bottom Conditions Assumed." Memoirs, College of Science, Kyoto Imperial Univ. (Series A), Vol. 16, pp. 333-351, 1933.

66. ___________, "Coast Effect Upon the Ocean Current and the Sea-Level: I. Steady State." Memoirs, College of Science, Kyoto Imperial Univ. (Series A), Vol. 16, pp. 93-144, 1934.

67. PANOFSKY, H. A., "Oceanography for the Navy Meteorologist." Navy Weather Research Facility, NWRF 32-0360-030, NAVWEPS 50-1P-547, 1960.

68. PATTULLO, J., W. MUNK, R. REVELLE and E. STRONG, "The Seasonal Oscillation in Sea Level." J. Mar. Rsch. 14(1), pp. 88-156, 1955.

69. PLATZMAN, G. W., "The Dynamical Prediction of Wind Tides on Lake Erie." Met. Monographs, Vol. 4, No. 26, 44 p., 1963.

70. PAWLIK, CHESTER L., et. al., "Texas Coast Hurricane Flood Protection Studies." American Society of Civil Engineers, Hydraulics Div., Journal, 93(6):147-168, 1967.

71. POLLOK, M. J., "Wind Set-Up and Shear-Stress Coefficient in Chesapeake Bay." J. Geophys. Rsch., 65(10), pp. 3383-3389, 1960.

72. PORE, N. A., "The Relation of Wind and Pressure to Extratropical Storm Surges at Atlantic City and Other East Coast Ports." J. Applied Met. 3(2), pp. 155-163, 1963.

73. ____________, A. T. ANGELO and J. G. TAYLOR, "Hurricane CINDY Galveston Bay Tides." U.S. Weather Bureau, Tech. Note, 11-TDL-2, 8 p., 1965.

74. ____________, "Chesapeake Bay Extratropical Storm Surges." Chesapeake Science, Solomans, MD., 6(3): 172-182, 1965.

75. PUTMAN, I. A., W. M. MUNK and M.A. TRAYLOR, "The Prediction of Long-Shore Current." Trans Amer. Geophys. Un. 30(3), pp. 337-345, 1949.

76. RAMANADHAM, R. and R. VARADARAJULU, "Storm Tides at Visakhapatnam." Indian Journal of Pure and Applied Physics, New Delhi, 3(5):173-176, 1965.

77. RATNAM, V. and P. S. NAYAR, "Floods Due to Storm Surges Associated With Cyclonic Storms." (In: Symposium on Hydrometeorology of India with Special Reference to Flood Forecasting and Warning, Proceedings. New Delhi, India, Meteorological Dept.). April 1966.

78. REDFIELD, A. C. and A. R. MILLER, "Water Levels Accompanying Atlantic Coast Hurricanes." Met. Monographs, Amer. Met. Soc., 2(10), pp. 1-23, 1957.

79. REID, ROBERT O., "Dynamic Storm-Tide Potential, Approximate Response of Water Level on a Sloping Shelf to a Wind Fetch Which Moves Directly Towards Shore." Tech. Rpt. No. 127-1 (Ref. 56-3T), Texas A&M Rsch. Foundation, 56 pp., 1956.

80. ____________, "Forced and Free Surges in a Narrow Basin of Variable Depth and Width, A Numerical Approach." Tech. Rpt. No. 153 (Ref. 57-25T), Texas A&M Rsch. Foundation, 60 pp., 1957.

81. ____________, "Effect of Coriolis Force on Edge Waves (I) Investigation of the Normal Modes." J. Mar. Rsch., 16(2), pp. 109-144, 1958.

82. ____________, "Modification of the Quadratic Bottom-Stress Law for Turbulent Channel Flow in the Presence of Surface Wind Stress." Technical Memorandum 93, U.S. Army Corps of Engineers, Beach Erosion Board, 33 p., 1957.

83. SAVILLE, T., JR., "Experimental Determination of Wave Set-Up." Proc., Second Tech. Conf. on Hurricanes, Natl. Hurr. Rsch. Proj. Rpt. No. 55, pp. 242-252, 1961.

84. SCHAFER, PEDRO, Jr., "Computation of a Storm Surge at Barrow, Alaska." Reprint from Archivfur Meteorologie, Geophysik and Bioklimatologie, Univ. of Washington, pp. 372-393, 1965.

85. SIELECKI, ANITA, "Studies of the Hydrodynamic Equations of Storm Surges, Jerusalem." Hebrew Univ., Dept. of Met., Contract CWB-11207, Report for 1st period of the project, 46 p., 1966.

86. ____________, "Energy-Conserving Difference Scheme for the Storm Surge Equations." Monthly Weather Review, Washington, D. C., 96(3):150-156, 1968.

87. STOMMEL, H., "A Survey of Ocean Current Theory." Deep-Sea Rsch. 4, pp. 149-184, 1957.

88. SVERDRUP, H. U., M. W. JOHNSON and R. H. FLEMING, "The Oceans, Their Physics, Chemistry and General Biology." Prentice-Hall, N.Y., 1087 pp., 1942.

89. THIEL, GUSTAV, "Die Sturmflut Der Nord-Und Ostsee Vol. 16, and 17, February 1962." [Storm Surges in the North and Baltic Seas, Feb. 16-17, 1962.] Deutsche Hydrographische Zeitchrift, Hamburg, 17(4): 174-178, August 1964.

90. U.S. COAST AND GEODETIC SURVEY, "Tide Tables, East Coast, North and South America." U.S. Dept. of Commerce, Current Edition.

91. U.S. FLEET WEATHER FACILITY, Jacksonville, Fla., "Annual Tropical Storm Report - 1957," OPNAV Rpt. 3140-9, 1957.

92. ____________, "Annual Tropical Storm Report - 1960." OPNAV Rpt. 3140-9, 1960.

93. VON ARX, W. S., "Introduction to Physical Oceanography." Addison-Wesley Publ. Co., Reading, Mass., 422 pp., 1962.

94. WELANDER, P., "Numerical Prediction of Storm Surges." Advances in Geophysics, Vol. 8, Academic Press, New York, pp. 315-379, 1961.

95. WILSON, BASIL W., "Model Study of Surge Action in a Port." (Table Bay Harbor, Cape Town, South Africa), Tech. Rpt. No. 24-(57) (Ref. 6-022T), Texas A&M Rsch. Foundation, 66 pp., 1960.

96. ____________, "Note on Surface Wind Stress Over Water at Low and High Wind Speeds." J. Geophys. Rsch. 65(10), pp. 3337-3382, 1960.

97. ____________, "The Prediction of Hurricane Storm Tides in New York Area." Tech. Rpt. No. 165-2 (Ref. 59-1F) Texas A&M Rsch. Foundation, 119 pp., 1959. "Comments on Paper by Basil W. Wilson, ___." by D. Lee Harris (closure by Author) Tech. Memo. No. 120-A Beach Erosion Board, Dept. of Army, Corps of Eng., 29 pp., 1961.

APPENDIX A

FORECAST CHECK-OFF LIST AND SAMPLE STORM-SURGE PREDICTION FOR LANDFALLING TROPICAL CYCLONES

1. Storm-Surge Forecast Check-Off List--Landfalling Tropical Cyclones

The check-off list presented below provides a logical format to follow in collecting the required data and in preparing a forecast of storm surge.

A. From the weather map

(1) Forecast the position of the storm center or eye and the minimum sea-level pressure at landfall. lat.________N/S

long.________W/E

____________mbs.

(2) Forecast speed of storm's movement. V_s________knots

(3) Forecast crossing angle of storm's track with respect to the coast at landfall. ________________°

(4) Forecast the radius of maximum winds (outer radius if maximum represents a broad band rather than a pronounced peak). ____________n.m.

(5) Forecast mean sea-level pressure drop. ____________mbs.

(6) Forecast time the eye will reach the coast. ________________Z

B. With the above parameters enter the circular nomograms, figures 7 through 15, to determine the precomputed storm-surge profile.

(1) Figure 7, distance from landfall to the peak storm surge. (A) ________ n.m.

(2) Figure 8, height of peak storm surge h_s for a standard storm. (B) h_s ________ ft.

(3) Figure 9, height of minimum storm surge*. (C) - ________ ft.

(4) Figure 10, distance of 1/2 storm-surge height to the right of the peak storm surge (as seen from seaward). (D) ________ n.m.

(5) Figure 11, distance of the 1/2 storm-surge height to the left of the peak storm surge (as seen from seaward). (E) ________ n.m.

(6) Figure 12, distance of the 1/4 storm-surge height to the right of the peak storm surge (as seen from seaward). (F) ________ n.m.

(7) Figure 13, distance of zero surge to the left of the peak storm surge (as seen from seaward). (G) ________ n.m.

(8) Figure 14, distance of the minimum surge to the left of the peak storm surge (as seen from seaward). (H) ________ n.m.

(9) Figure 15, peak storm-surge arrival time in minutes after landfall (negative numbers mean peak storm surge occurs before landfall). ________ min.

*Note: The time of the storm surge pertains only to the peak surge. The minimum surge height is the hardest to forecast accurately; may not occur at the time of peak surge; is transitory; and can eventually turn into respectable positive values after the passage of the storm.

C. Correcting the precomputed storm surge for actual conditions

(1) Enter figure 16 with the average sea-level pressure drop and the radius of maximum winds, read the Wind Field Correction Factor V_R. V_R ________ kts.

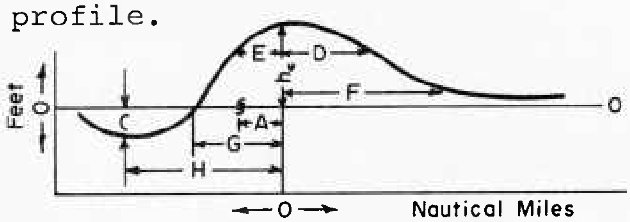
(2) Determine Depth Profile Correction Factor F_D for landfall position. F_D ________

(3) Solve peak storm-surge equation for corrected storm-surge height.

$$h_c = h_s \left(\frac{V_R}{87}\right)^2 F_D$$

h_c ________ ft.

(4) Construct the storm-surge profile.



(5) The above data are sufficient to issue a preliminary storm-surge warning; e.g., HURRICANE (Typhoon) BOGUS. PRELIMINARY STORM-SURGE WARNING. HEIGHTS IN FEET ABOVE NORMAL TIDES. PEAK SURGE OF 16 FEET 25 MILES EAST OF LANDFALL DECREASING TO 8 FEET 60 MILES EAST AND 5 MILES WEST; AND TO 4 FEET 110 MILES EAST OF LANDFALL. TRANSITORY MINIMUM SURGE OF MINUS 4 FEET NEAR 80 MILES WEST OF LANDFALL.

To decrease the possibility of consumer confusion, the surge parameters are related to the landfall position only.

D. Final Storm-Surge Forecast

Depending upon the characteristics of the storm, the storm surge is going to start along the coast 24 to

48 hours in advance of the landfall. This slow rise in water level and increase in swell is called the forerunner. The computed storm-surge profile as constructed in paragraph C.4. is valid for the inshore boundary of the standard basin - a straight boundary with a water depth of 15 feet. As the time to landfall decreases, the landfall position and the storm characteristics can be more accurately forecast; and a better estimate can be made of the inshore features which have a major controlling effect on the actual water heights. Consideration should be given the inshore topography at the earliest possible time, including the low-lying coastal areas that may be underwater during the storm surge. The effect of the additional factors listed below, which in proper combination may more than double the computed storm surge, should be carefully examined when issuing a storm-surge forecast for a particular position or area.

(1)	Astronomical tide	high: time______	ft._____
		low: time______	ft._____
(2)	Mean sea-level anomaly		______ft.
(3)	Wind stress		______ft.
(4)	Wave set-up and refraction		______ft.
(5)	Rain		______in./hr.

2. Sample Forecast for a Hurricane Landfalling on an Island Chain and the Effects on an Enclosed Body of Water

Hurricane DONNA made landfall along the Florida Keys at 0700Z on 10 September. At that time the minimum pressure was 939 millibars with an eye diameter of 27 miles. Winds were reported to be between 120 and 140 knots, with 65-knot winds extending 100 miles to the northeast of the eye. DONNA was moving northwest at 9 knots. The first anticyclonically turning isobar was 1012 millibars, figure A-1, which gives a pressure drop of 73 millibars.

The relative 0° - 180° crossing angle line has been inscribed along the Florida Keys in figure A-2. It is with respect to this line that the storm-surge profile is plotted in this example, and which is used as a reference for computing the data entered on the storm-surge check-off list.

The remaining data are read from the appropriate nomograms and entered on the check-off list. When the check-off list is complete the data may be entered along the storm-surge line. Caution: Distances are measured relative to the peak-surge point. The storm-surge profile is only valid at the time of the peak surge, and will not coincide with the high-water marks which represent maximum water levels reached at some unspecified other time during the passage of the hurricane. High-water mark data are measured from mean sea level.

With a line of low islands and a relatively narrow coastal shelf, the effects of wind stress were decreased somewhat over what would be expected with a wide, shallow, coastal

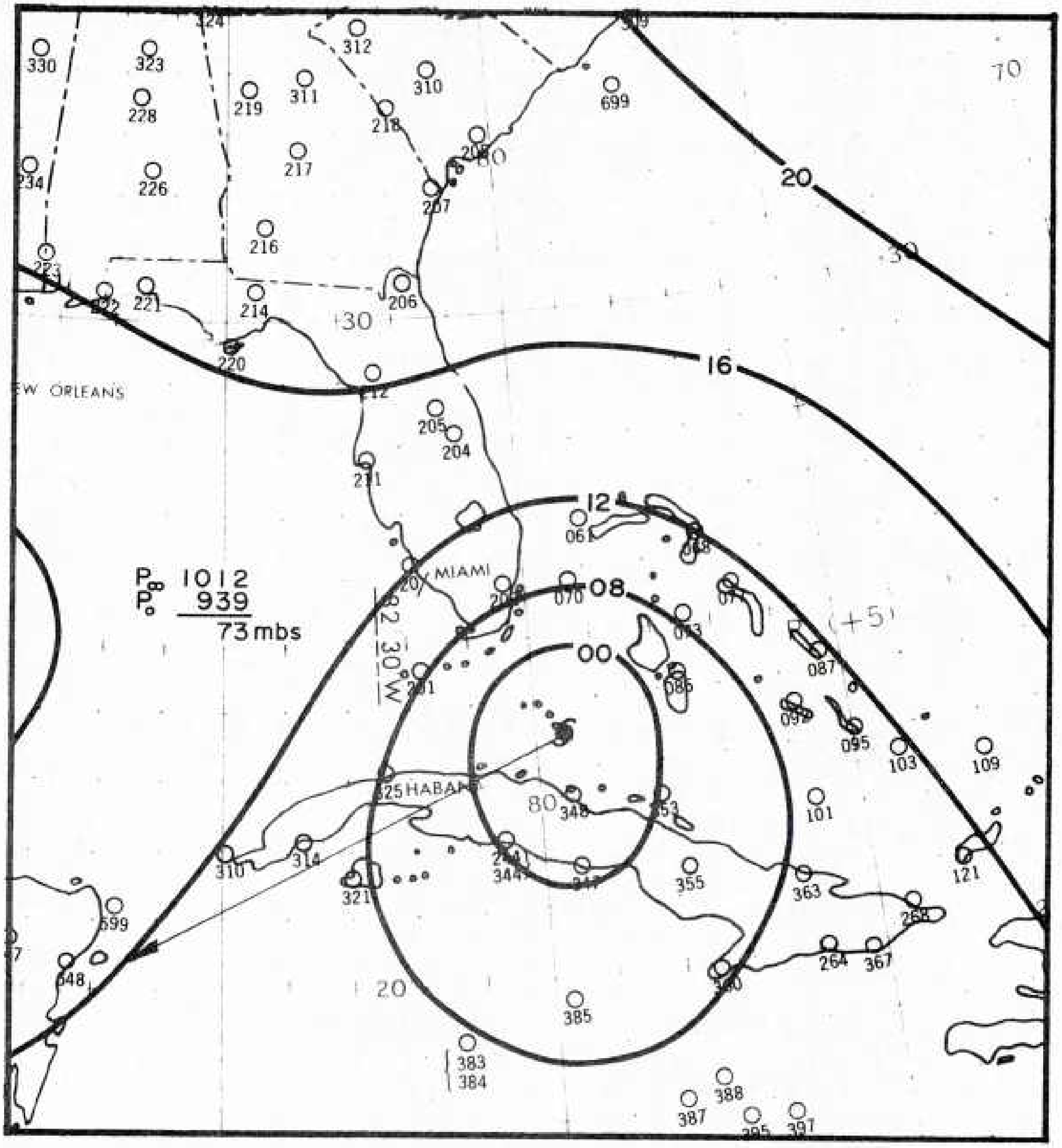


Figure A-1. Hurricane DONNA 1960, September 9-13. Synoptic Charts (after Harris [30]).

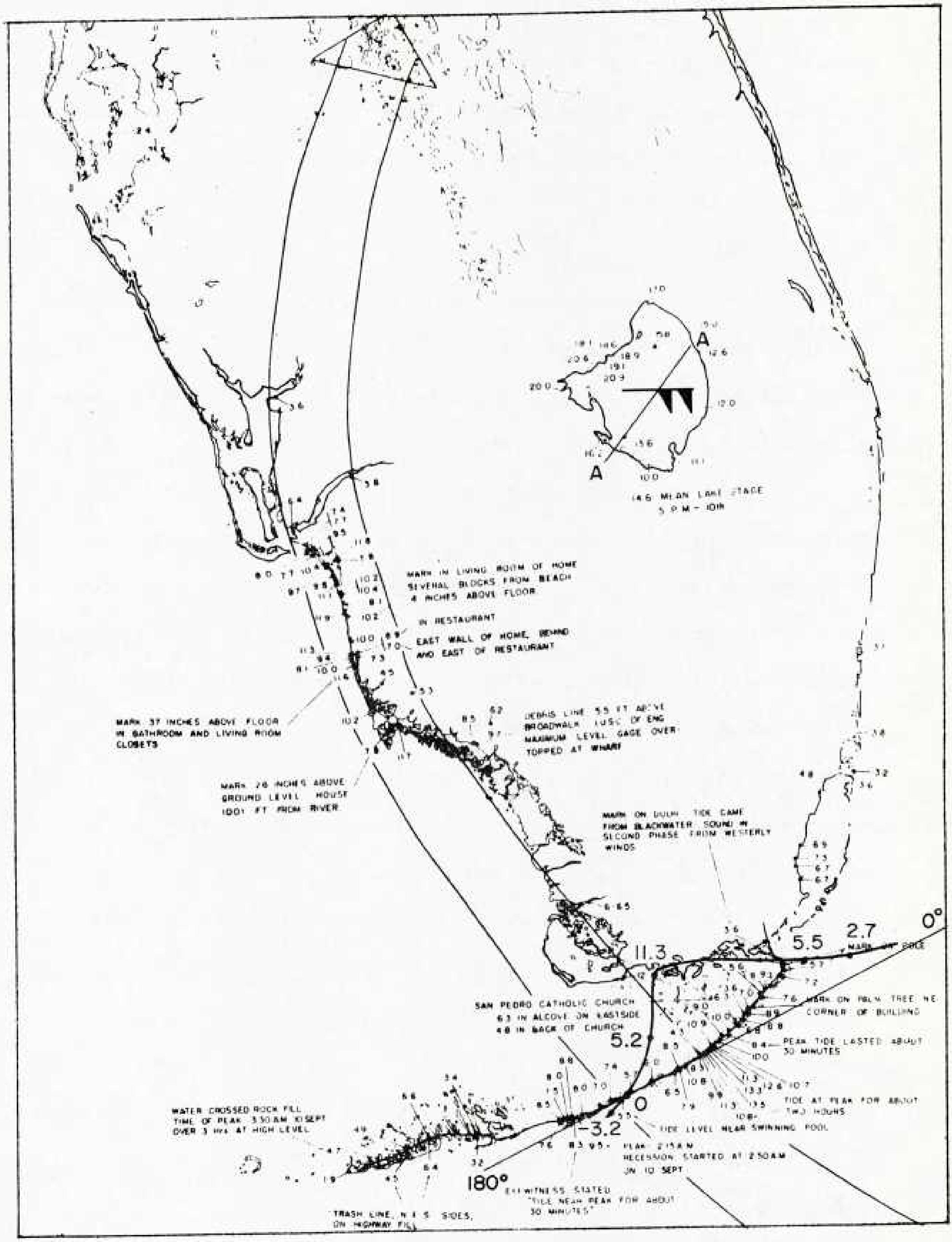


Figure A-2. Hurricane DONNA 1960, September 9-13. High Water Mark Chart for Florida. (Based on data obtained from the Jacksonville District of the U.S. Army Corps of Engineers) (after Harris [30]).

shelf. Wave set-up is probably a major contributor to the high-water marks on the islands where there is a minimum of coastline against which the wind stress can act. The high-water marks on the San Pedro Catholic Church, to the north of the peak-surge point in figure A-2, shows a water mark 1.5 feet higher on the windward than on the leeward side of the church within a distance of less than 50 feet -- revealing the small scale of the dynamic features affecting the high-water mark data.

The peak storm-surge height, indicated by the plotted storm-surge profile shown as a dashed line in figure A-2, was computed to be 11.1 feet (see Hurricane DONNA check-off list). From post-storm analysis, the actual high-water marks reported within several miles of the projected onshore point on the computed peak storm-surge height, ranged from 10.7 to 13.5 feet. This small differential between corrected and observed storm-surge heights of from -0.4 to 2.4 feet shows skill, in consideration of the storm-surge forecast having been prepared with limited, readily available data. The application of subjective corrections for effects inshore from the inner standard-basin boundary could possibly have reduced the size of this differential. For example, since the keys are mostly small, flat, low-lying islands, wind stress and rain would be somewhat less of a factor than would ordinarily be expected along a continuous coastline.

STORM-SURGE FORECAST CHECK-OFF LIST -- LANDFALLING TROPICAL CYCLONE

HURRICANE DONNA
10 Sep 1960

A. From the weather map

(1) Forecast the position of the storm center or eye and the minimum sea-level pressure at landfall. lat. 24°-57'N/~~S~~

long. 80°-40' W/~~E~~

939 mbs.

(2) Forecast speed of storm's movement. V_s 9 knots

(3) Forecast crossing angle of storm's track with respect to the coast at landfall. 80 °

(4) Forecast the radius of maximum winds (outer radius if maximum represents a broad band rather than a pronounced peak). 15 n.m.

(5) Forecast mean sea-level pressure drop. 73 mbs.

(6) Forecast time the eye will reach the coast. 0700 Z

10 Sep 1960

B. With the above parameters enter the circular nomograms, figure 7 through 15, to develop the precomputed storm-surge profile

(1) Figure 7, distance from landfall to the peak storm surge. (A) 17 n.m.

(2) Figure 8, height of peak storm surge h_s for a standard storm. (B) 9.5 ft.

(3) Figure 9, height of minimum storm surge*. (C) -3.2 ft.

(4) Figure 10, distance of 1/2 storm-surge height to the right of the peak storm surge (as seen from seaward). (D) 28 n.m.

(5) Figure 11, distance of the 1/2 storm-surge height to the left of the peak storm surge (as seen from seaward). (E) 13 n.m.

(6) Figure 12, distance of the 1/4 storm-surge height to the right of the peak storm surge (as seen from seaward). (F) 48 n.m.

(7) Figure 13, distance of zero surge to the left of the peak storm surge (as seen from seaward). (G) 22 n.m.

(8) Figure 14, distance of the minimum surge to the left of the peak storm surge (as seen from seaward). (H) 34 n.m.

(9) Figure 15, peak storm-surge arrival time in minutes after landfall (negative numbers mean peak storm surge occurs before landfall). -10 min.

*Note: The time of the storm surge pertains only to the peak surge. The minimum surge height is the hardest to forecast accurately; may not occur at the time of peak surge; is transitory; and can eventually turn into respectable positive values after the passage of the storm.

C. Correcting the precomputed storm surge for actual conditions

(1) Enter figure 16 with the average sea-level pressure drop and the radius of maximum winds, read the Wind Field Correction Factor V_R. V_R 100 kts.

(2) Determine Depth Profile Correction Factor F_D for landfall position. F_D 0.90

(3) Solve peak storm-surge equation for corrected storm-surge height. h_c 11.1 ft.

$$h_c = h_s \left(\frac{V_R}{87}\right)^2 F_D$$

$$= 9.5 \left(\frac{100}{87}\right)^2 0.9$$

$$= 9.5\ (1.2)\ 0.9 = 11.1$$

3. Sample Forecast for a Hurricane Landfalling on a Low Coast and River Delta

The forecast of the actual water level for any specific point in an area affected by storm surge is extremely complex. A typical example of a storm-surge analysis for a low-lying coast with a river delta is the very well-documented case of Hurricane AUDREY, 26-27 June 1957.

Hurricane AUDREY formed in the Bay of Campeche on 24 June and moved northerly until it crossed the coast a few miles east of Cameron, Louisiana -- 17 miles east of the Texas-Louisiana border.

The coastline in southwestern Louisiana consists of narrow ridges, mostly parallel to the coast, that are frequently no more than 100 feet across and less than 3 feet above mean sea level. North of the ridges, the land drops quickly to approximately sea level or below. As shown in figure A-3, the first continuous 5-foot contour may be 15 to 20 miles inland from the coastal ridges. When such an area is inundated by a storm surge, the once dry-land topography then becomes part of the bottom configuration which influences the waves and currents associated with storm surge.

The lowest official pressure reported at the time the hurricane passed over the coast was 960 millibars. Maximum sustained winds were 95 knots. Post-hurricane reports [28] indicate that the pressure may have been lower and the wind may have been higher. Using these data and that available

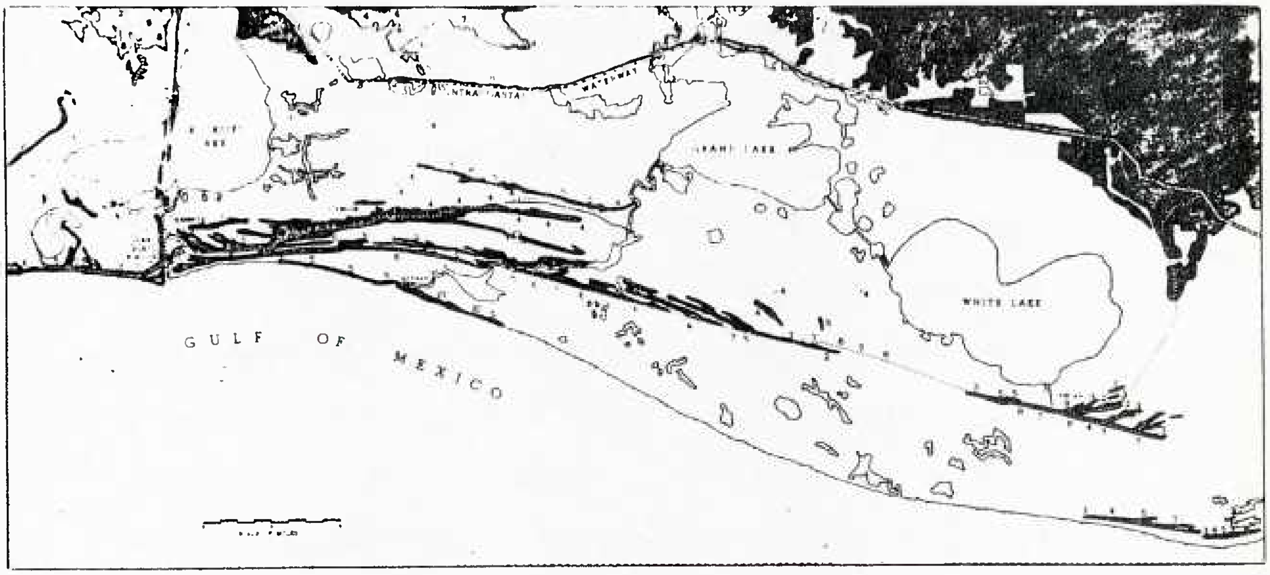


Figure A-3. Hurricane AUDREY 1957, June 26-27. Topography of Southern Louisiana (after Harris [30]).

from the weather map, figure A-4, the pressure drop of the storm was estimated to be 44 millibars.

It should be noted, that this storm is considerably larger than the model storm [43], figure 3, where the radius of the 35-knot wind circle is only 87 miles. In Hurricane AUDREY, 35-knot winds extended about 200 miles to the east, to approximately 91° W. longitude. This would have the effect of extending the storm surge eastward along the coast.

The bottom slope decreases to the east, increasing F_D as shown in figure 18, thereby increasing the computed height of the storm surge in the eastern area. The storm-surge profile, as deduced from the check-off list which is included at the end of this section, is depicted in figures A-5 and A-6.

Note that the 1/2 and 1/4 surge heights have been increased to include the increased bottom-slope depth-correction factor F_D, but that an extension of the storm surge farther along the coast because of the large size of the storm was not added to the profile. This could easily have accounted for the resulting surge heights along the coast as far east as the Mississippi River Delta.

The peak surge, which is related to the radius of maximun wind, was 13.9 feet and occurred a few miles east of the 10.3-foot corrected peak surge. The 3.6 foot difference is smaller than might be expected from the combined wind stress

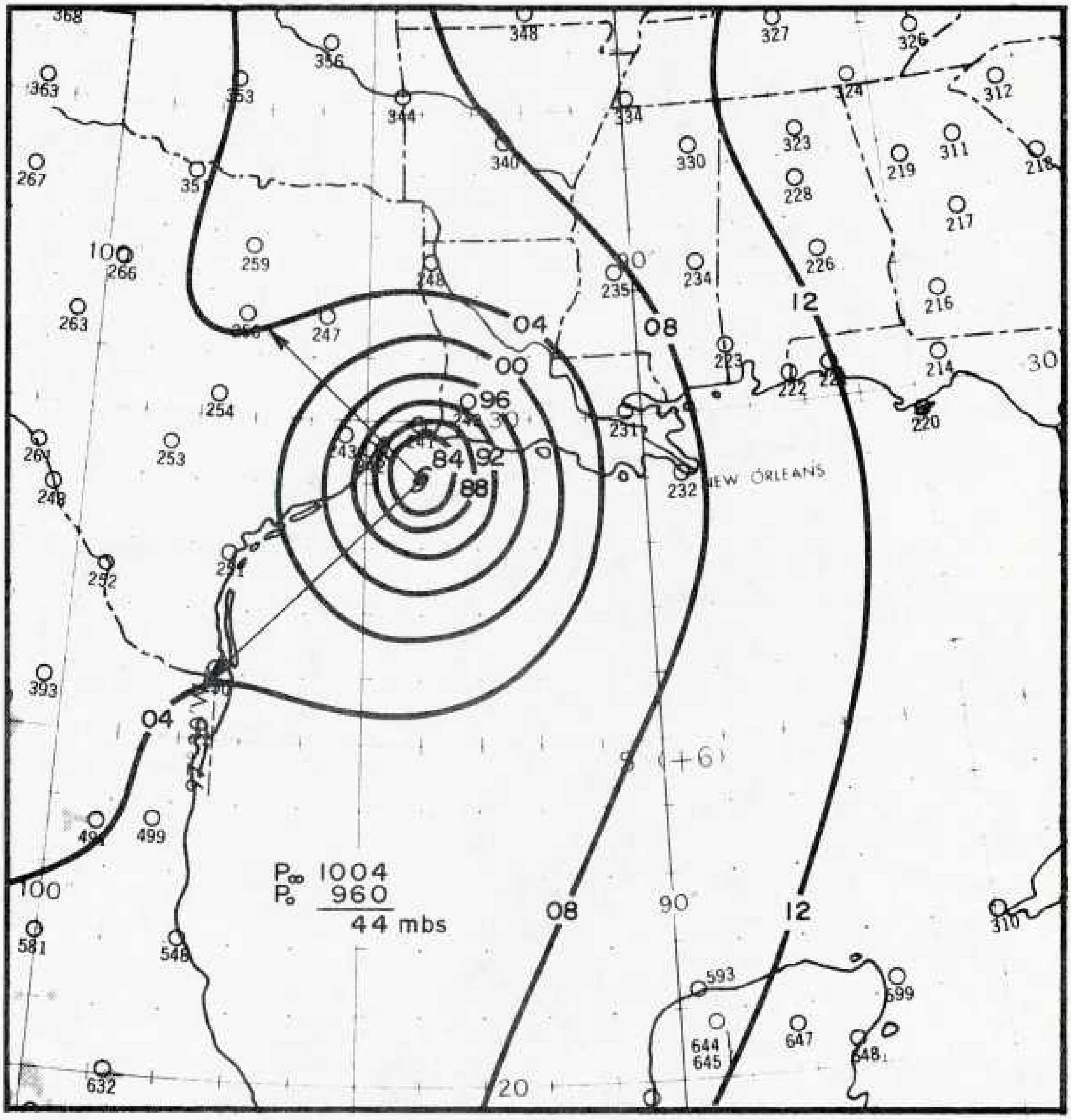


Figure A-4. Hurricane AUDREY 1957, June 26-27. Synoptic Charts (after Harris [30]).

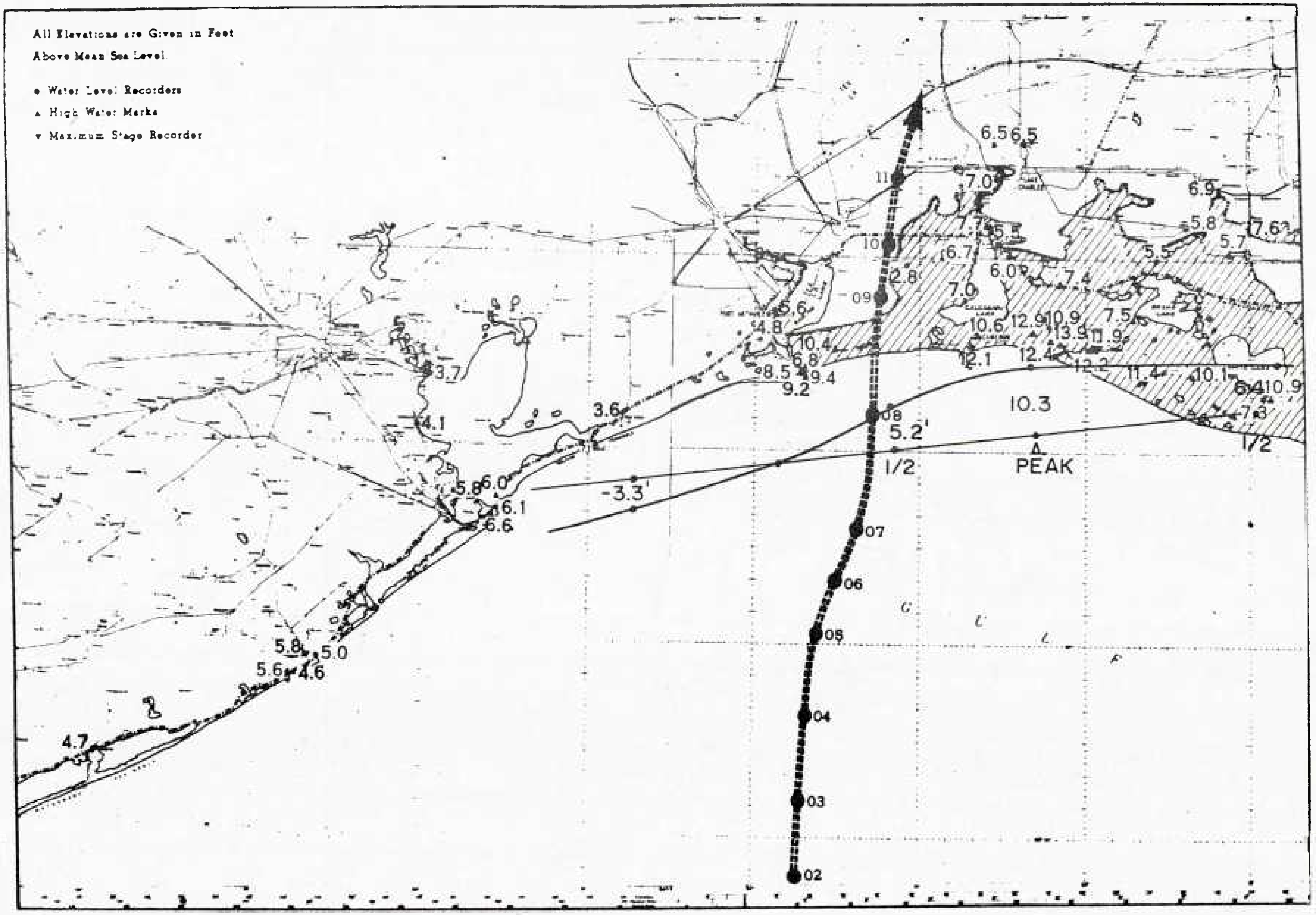


Figure A-5. Hurricane AUDREY 1957, June 26-27. High Water Mark Chart for Texas and Western Louisiana. Hatched Area Gives Limit of Inundation in Louisiana (after Harris [30]).

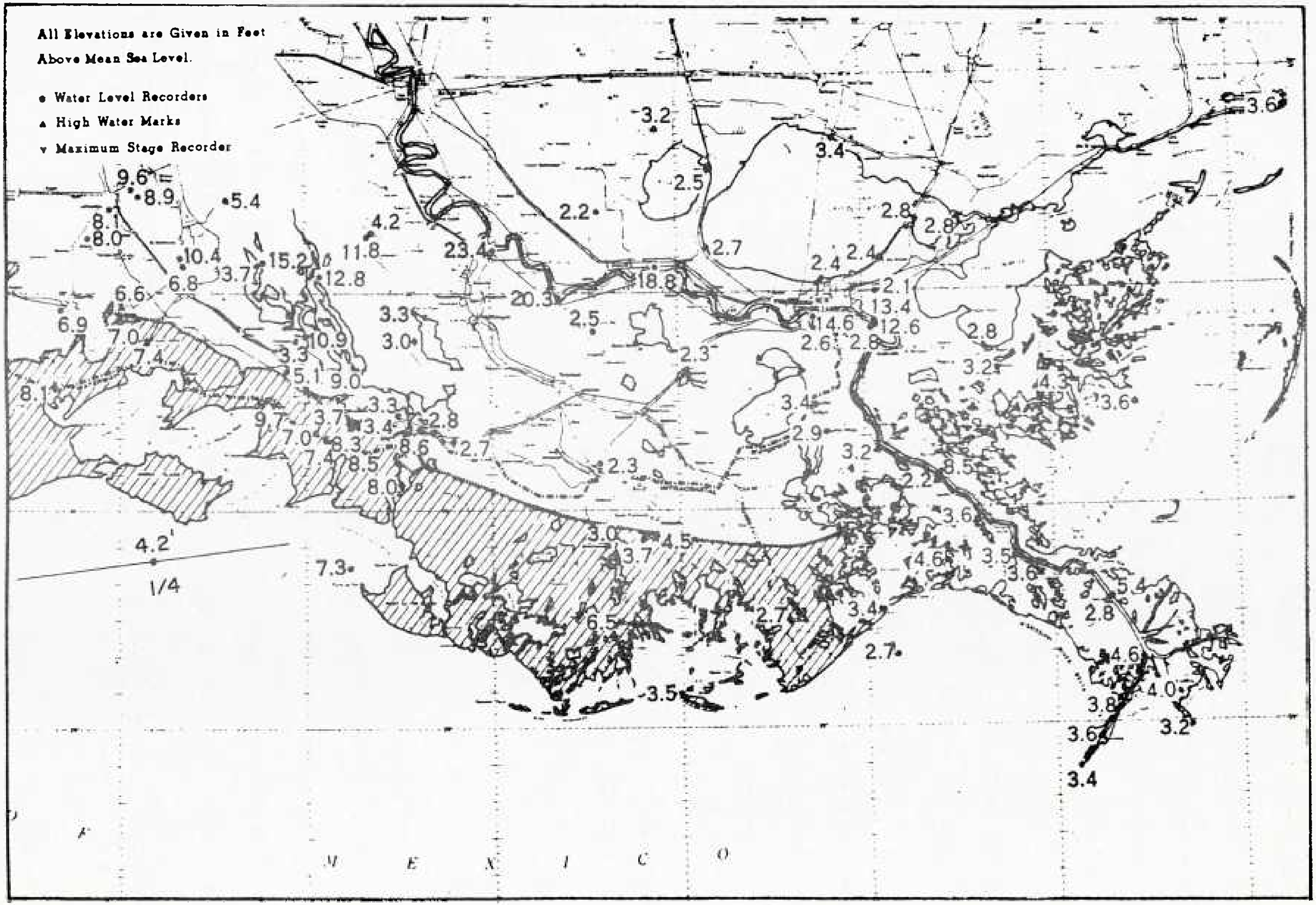


Figure A-6. Hurricane AUDREY 1957, June 26-27. High Water Mark Chart, Eastern Louisiana. Hatched Area Gives Limit of Inundation in Louisiana (after Harris [30]).

and wave set-up in so large a hurricane; however, the smaller than expected storm-surge height might be explained by the extreme flatness of the inundated littoral plain. Without a sloping shore there is nothing to react upon, and the water is forced inland without peaking. This possibility is suggested by many of the tide and flood gauge records and eyewitness reports. The water level north of the ridges was actually depressed before the storm surge topped the levees and low ridges, followed by a rapid rise to a height a few feet above the ridges.

Atchafalaya Bay and the ocean for 30 to 50 miles offshore is less than 20 feet deep, so the 7.3-foot high-water mark west of Point au Fer is probably due to the combined effects of the surge, wind stress, and extremely high waves over the bar which extends across the mouth of the bay to the northwest.

The high-water marks north of Atchafalaya Bay in figure A-6 are possibly caused by wave set-up along the windward sides of the ridges. The lower water marks in the lee of the ridges are along the windward shores of Grand Lake (the one north of Atchafalaya Bay; there are two Grand Lakes in Louisiana, the other is shown in figure A-5). Wind stress has prevented the water level from reaching much over 3 feet on the windward end of the lake; yet, at the opposite end of the lake, the wind has driven the surge to a height of 15.2 feet.

Rain can be a very substantial factor in any storm-surge calculation. The high-water marks away from the coast in figure A-6 are flood stages from rain. The run-off into the Mississippi River produced a flood crest of 23.4 feet at Donaldsonville, Louisiana, with lower crests downriver. Torrential rains from the remnants of Hurricane CAMILLE, 1969, were the cause of a disastrous flood in the mountains of Virginia, where wind and storm surge were not factors.

STORM-SURGE FORECAST CHECK-OFF LIST -- LANDFALLING TROPICAL CYCLONES

HURRICANE AUDREY
27 June 1957

A. From the weather map

(1) Forecast the position of the storm center or eye and the minimum sea-level pressure at landfall. lat. 29°-45' N/~~S~~

long. 093°-37' W/~~E~~

960 mbs.

(2) Forecast speed of storm's movement. V_s 12 knots

(3) Forecast crossing angle of storm's track with respect to the coast at landfall. 95 °

(4) Forecast the radius of maximum winds (outer radius if maximum represents a broad band rather than a pronounced peak). 30 n.m.

(5) Forecast mean sea-level pressure drop. 44 mbs.

(6) Forecast time the eye will reach the coast. 1400 Z

27 June 1957

B. With the above parameters enter the circular nomograms, figure 7 through 15, to develop the precomputed storm-surge profile

(1) Figure 7, distance from landfall to the peak storm surge. (A) 24 n.m.

(2) Figure 8, height of peak storm surge h_s for a standard storm. (B) 13 ft.

(3) Figure 9, height of minimum storm surge*. (C) -3.8 ft.

(4) Figure 10, distance of 1/2 storm-surge height to the right of the peak storm surge (as seen from seaward). (D) 40 n.m.

(5) Figure 11, distance of the 1/2 storm-surge height to the left of the peak storm surge (as seen from seaward). (E) 24 n.m.

(6) Figure 12, distance of the 1/4 storm-surge height to the right of the peak storm surge (as seen from seaward). (F) 70 n.m.

(7) Figure 13, distance of zero surge to the left of the peak storm surge (as seen from seaward). (G) 44 n.m.

(8) Figure 14, distance of the minimum surge to the left of the peak storm surge (as seen from seaward). (H) 72 n.m.

(9) Figure 15, peak storm-surge arrival time in minutes after landfall (negative numbers mean peak storm surge occurs before landfall). -40 min.

*Note: The time of the storm surge pertains only to the peak surge. The minimum surge height is the hardest to forecast accurately; may not occur at the time of peak surge; is transitory; and can eventually turn into respectable positive values after the passage of the storm.

C. Correcting the precomputed storm surge for actual conditions

(1) Enter figure 16 with the average sea-level pressure drop and the radius of maximum winds, read the Wind Field Correction Factor V_R. V_R 67 kts.

(2) Determine Depth Profile Correction Factor F_D for landfall position. F_D 1.34

(3) Solve peak storm-surge equation for corrected storm-surge height. h_c 10.28 ft.

$$h_c = h_s \left(\frac{V_R}{87}\right)^2 F_D$$

$$= 13 \left(\frac{67}{87}\right)^2 1.34$$

$$= 13\ (.59)\ 1.34 = 10.28$$

APPENDIX B

FORECAST CHECK-OFF LIST AND SAMPLE STORM-SURGE PREDICTION FOR NON-LANDFALLING TROPICAL CYCLONES

Tropical cyclones that stagnate, loop, recurve or in any way fail to landfall are considered as travelling parallel to the coast. The problem has been further simplified by restricting the description of surges from these storms to the moving, directly generated surge (the first crest and trough of the coastal surge profile associated with the storm's center and moving with the storm). Only storms moving along the coast with land to the left are considered.

Figure B-1 is the nomogram used to determine the directly generated surge for a standard storm travelling parallel to the coast over a standard basin. Let the radius of maximum winds be 30 miles; other values of this parameter need not be considered, since only the peak surge is to be forecast. At large distances from the coast, slowly moving storms have higher surges (since there is more time for the surge to build); but near the coast fast-moving storms have higher surges. One should be careful in accepting the directly generated trough as fully representative, since such factors as: storms that vary in strength, size and speed; depths varying in two dimensions; curvilinear coasts; and the effect of various depth profiles on resurgences have not been considered. In the model these resurgences (edge waves) do not become important unless the storm is moving very fast

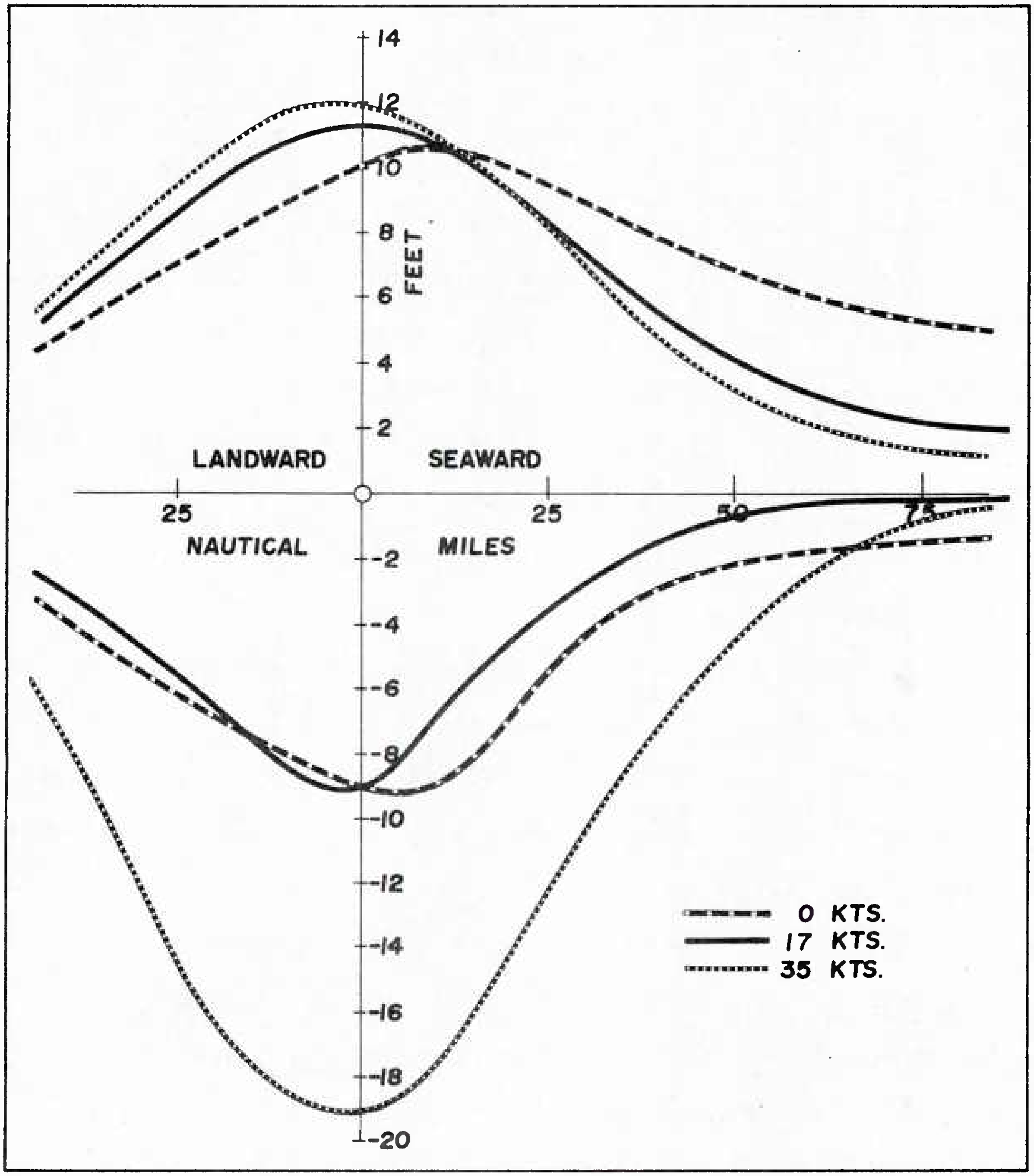


Figure B-1. For Storms Paralleling the Coast the Precomputed Height of the Directly Generated Surge Is Determined by Entering the Nomogram: (1) With the Closest Point of Approach (CPA) Along the Abscissa, (2) Moving Vertically Above and Below the CPA Line to the Storm Speed of Motion and (3) Reading the Height of the Crest (above) and the Trough (below) of the Directly Generated Surge Height for the Standard Storm h_s (after Jelesnianski [44]).

(over 35 knots) with the center slightly seaward of the coast. The height of the first resurgence would be less than half of the directly generated crest at maximum.

1. Storm-Surge Forecast Check-Off List -- Non-Landfalling Tropical Cyclones

   A. From the weather maps:

      (1) Forecast the storm track to determine the closest point of approach (CPA) to the locale for which the prediction will be made. CPA ________ n.m.

      (2) Forecast average storm speed. ________ knots

      (3) Forecast the average sea-level pressure decrease, using the same procedure as for storms that landfall. ________ mbs.

   B. Enter figure B-1 with the CPA and storm speed; read the peak-surge height h_s and the trough height h_t for a standard storm.

      h_s ________ ft.

      h_t ________ ft.

   C. Enter figure 16 with a 30-mile radius of maximum wind and mean sea-level pressure drop of the storm; read Wind Field Correction Factor V_R. V_R ________ knots

   D. Determine Depth Profile Correction Factor F_D from figures 17 or 18. F_D ________

   E. Solve the storm-surge equation for the computed storm surge at the inner standard-basin boundary.

$$h_c = h_s \left(\frac{V_R}{87}\right)^2 F_D$$

	crest	trough
h_c	____ ft.	____ ft.

   F. Based upon local conditions, add the following factors as appropriate to arrive at storm-surge forecast:

(1) Astronomical tide, high: time ______, _______ft.

low: time ______, _______ft.

(2) Sea-level anomalies _______ft.

(3) Wind stress _______ft.

(4) Wave set-up and refraction _______ft.

(5) Rain _____ inches/hour _______ft.

2. Sample Forecast for a Non-Landfalling Hurricane

Hurricane DONNA, 9-13 September 1960, provides a very interesting example of a non-landfalling storm (as well as of the effects of an island chain discussed in appendix A). After passing over Florida, DONNA essentially paralleled the coast of Georgia and South Carolina while increasing in size and intensity. DONNA cut across the tip of North Carolina, and then paralleled the coast again until landfall was made on Long Island. The track shown on figure B-2 also shows a steady increase in storm speed from the time DONNA passed off the east coast of Florida.

Myrtle Beach was chosen for the sample problem, because the tide gauge there has better exposure than at Charleston or Fort Pulaski which are on rivers or bays. Fort Pulaski and Savannah are subject to complex surge conditions, owing to the many channels and islands in the bay and river mouth. Fernandina and Mayport were in an area of rapid hurricane reformation, and conditions had not stabilized.

The check-off list for the Myrtle Beach forecast included at the end of this appendix is straight forward. Figure B-1 is used in place of the nine circular nomagrams required for landfalling tropical cyclones. The corrected peak-surge height h_c is only 0.3 feet less than the observed surge h_o at Myrtle Beach.

Hurricane DONNA still had winds over 110 knots upon passing off the North Carolina coast, and forward speed was

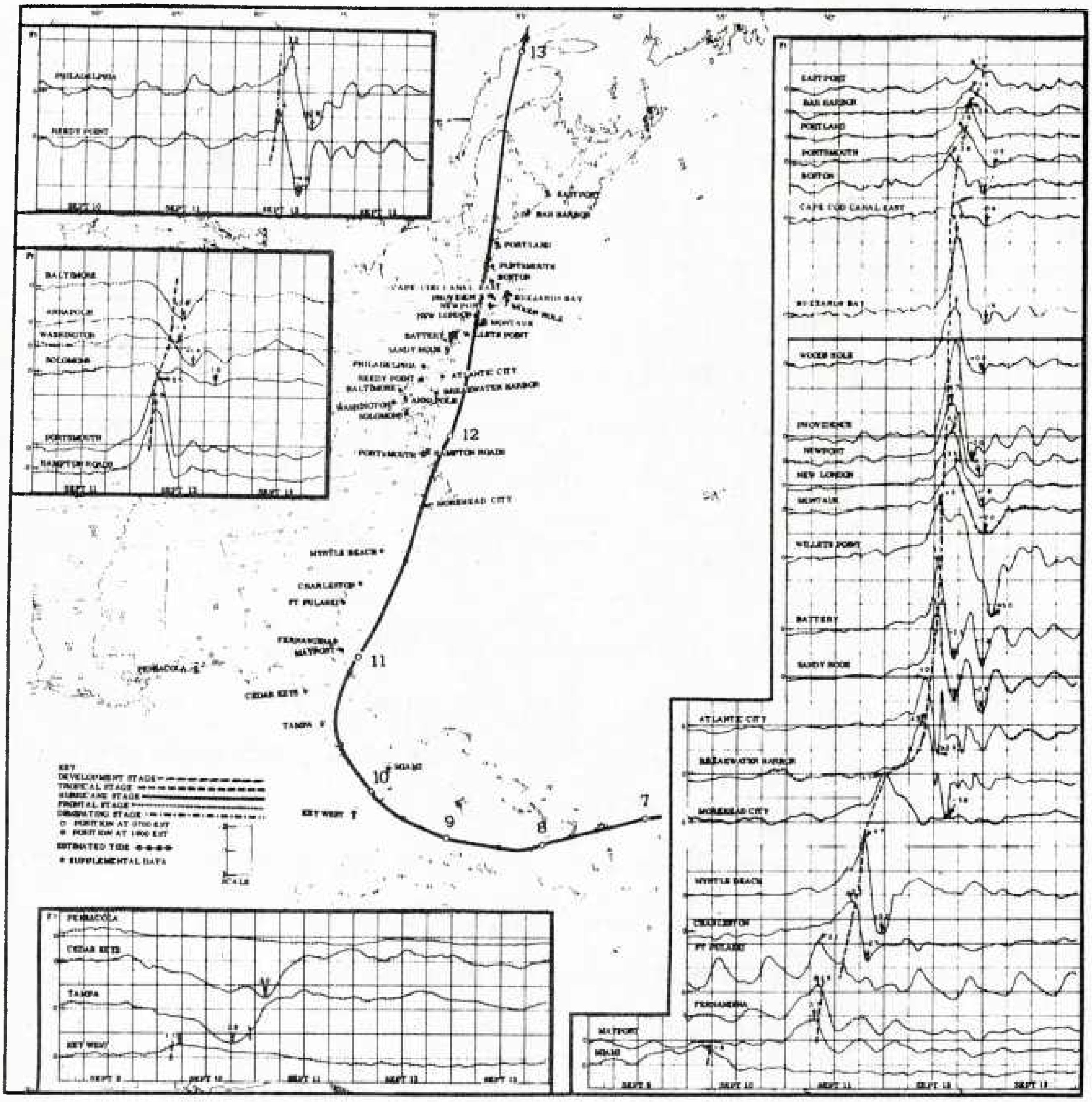


Figure B-2. Hurricane DONNA 1960, September 9-13. Storm-Surge Chart (after Harris [30]).

rapidly increasing. Resurgences are apparent from Breakwater Harbor through the Battery. The storm surge at Willets Point showed the double peak typical of that locale, with the second surge arriving via Long Island Sound. The 8.0-foot surge at Providence and the 6.5-foot surge at Buzzards Bay are prime examples of peaking of the storm surge caused by the convergence of the shoreline from the mouth to the head of a bay.

The storm-surge graphs on the left side of figure B-2 illustrate a variety of special situations. Particularly noteworthy are: Philadelphia, with a late crest followed shortly by a -2.9-foot trough; Washington, with a -1.4-foot trough followed by a long-period crest and trough as the Potomac River adjusts to rainfall runoff and seiching effects; and the troughs of -3.0-feet and -2.8-feet at Cedar Keys and Tampa, respectively, on the west coast of Florida. An exhaustive study for each individual location, including attention to variations in channel directions and in the wind field during the period of DONNA's passage, could provide subjective explanations for the high-water marks that occurred; but the complexity of the geography and bathymetry would make detailed quantitative predictions almost impossible if not unrealistic in view of existing hurricane forecasting deficiencies.

STORM-SURGE FORECAST CHECK-OFF LIST -- NON-LANDFALLING TROPICAL CYCLONES

HURRICANE DONNA
11 Sep 1960

A. From the weather map

(1) Forecast the storm track to determine the closest point of approach (CPA) to the locale for which the prediction will be made. — CPA 45 n.m.

(2) Forecast average storm speed. — 20 knots

(3) Forecast the average sea-level pressure decrease, using the same procedure as for storms that landfall. — 52 mbs.

B. Enter figure B-1 with the CPA and storm speed; read the peak-surge height h_s and the trough height h_t for a standard storm. — h_s 5 ft.

h_t -1.9 ft.

C. Enter figure 16 with a 30-mile radius of maximum wind and mean sea-level pressure drop of the storm; read Wind Field Correction Factor V_R. — V_R 73 knots

D. Determine Depth Profile Correction Factor F_D from figure 17. — F_D 1.25

E. Solve the storm-surge equation for the computed storm surge at the inner standard-basin boundary.

	crest	trough
h_c	4.4 ft.	-1.2 ft.
h_o	4.7 ft.	-3.2 ft.

$$h_c = h_s \left(\frac{V_R}{87}\right)^2 F_D$$

$$5\ (.84)^2\ 1.25 = 4.4$$

APPENDIX C

FORECAST CHECK-OFF LIST AND SAMPLE STORM-SURGE PREDICTION FOR EXTRATROPICAL STORMS

Jelesnianski [43, 44] does not mention the applicability of his method to extratropical storms; in fact, the dimensions which he imposes upon his standard storm seems to preclude consideration of this method for extratropical storms. However, it was found that the method showed some skill if allowances were made for the differences between tropical and extratropical systems.

The extratropical storm must be somewhat circular in shape (at least, the central portion must have circular closed isobars), or another method for forecasting storm surge should be selected. The pressure gradient in an extratropical storm will normally be shallower than in a tropical cyclone; however the maximum wind, even though lower in an extratropical storm, extends over a much larger area. This results in a lower peak surge, but a much larger dispersion along the coast.

With the longer fetches of the extratropical storm, wind stress and wave set-up become increasingly important. Local climatological records, rules of thumb or statistical derivations such as those developed by Miller [56] for estimating wind-induced wave set-up at Atlantic City (fig. C-1) are particularly useful in storm-surge forecasting.

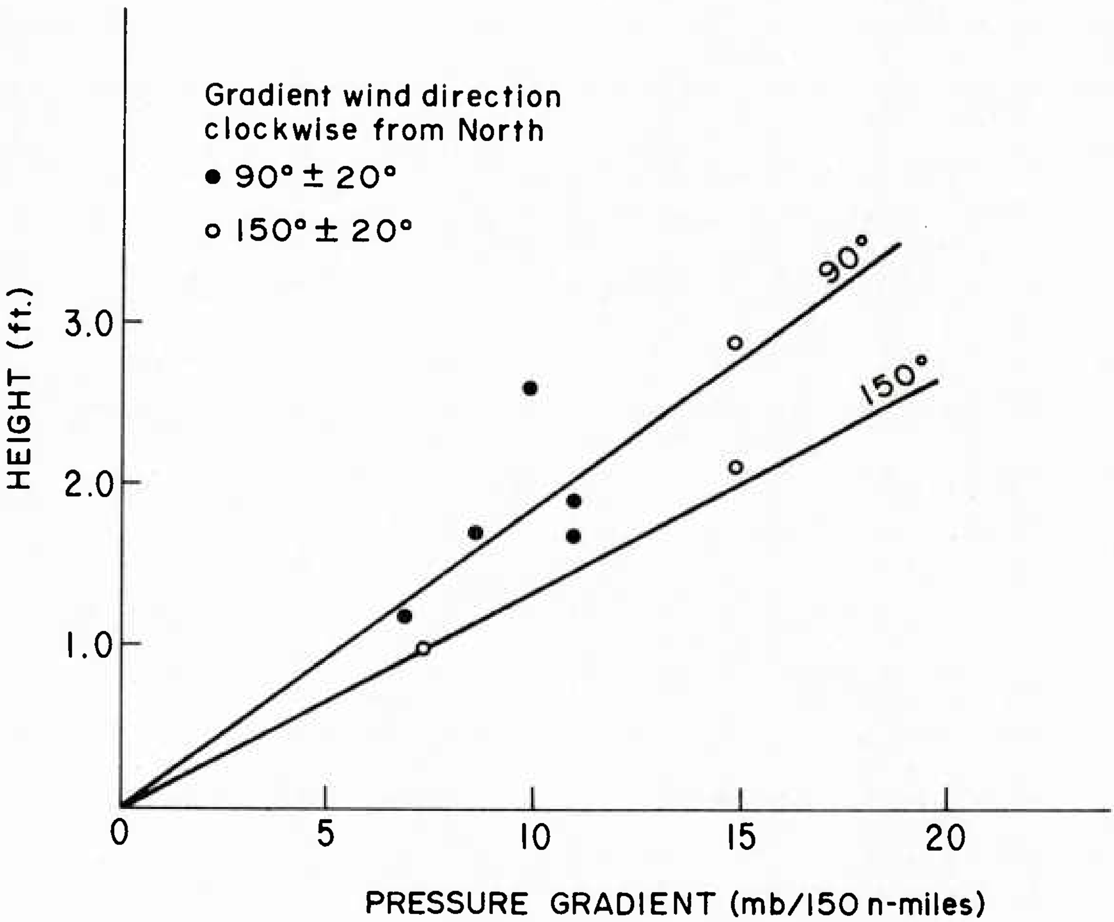


Figure C-1. Wind Induced Wave Set-Up at Atlantic City (after Miller [56]).

It would be more accurate for a particular locality to start with an actual occurrence of storm surge and relate it to the environmental conditions, rather than the reverse procedure. In many areas (rivers, sheltered bays or bayous) this may be the only way to ascertain the sea-level reaction to the environment, because of the complex bottom topography and basin configurations.

In this instance an extratropical storm has developed off Cape Hatteras and tracked northward, crossing the coast at New York City as shown in figure C-2. A storm surge in the New York City - Long Island area is a special case that would be a study in itself, and will not be attempted in this general presentation. However, the storm surge at Atlantic City was well documented, and provides an example of storm-surge prediction for both an extratropical storm and a non-landfalling storm.

The first and most obvious problem is the determination of pressure drop across the storm. The gradient over the inner part of the storm will likely be approximately the same as that within 100 miles of the center.

Determining the outer periphery pressure is more troublesome. Fronts frequently deform the isobars so that they recurve anticyclonically quite near the center. Therefore, the quadrant where the fronts are located must be arbitrarily avoided in determining the pressure drop for the storm. In

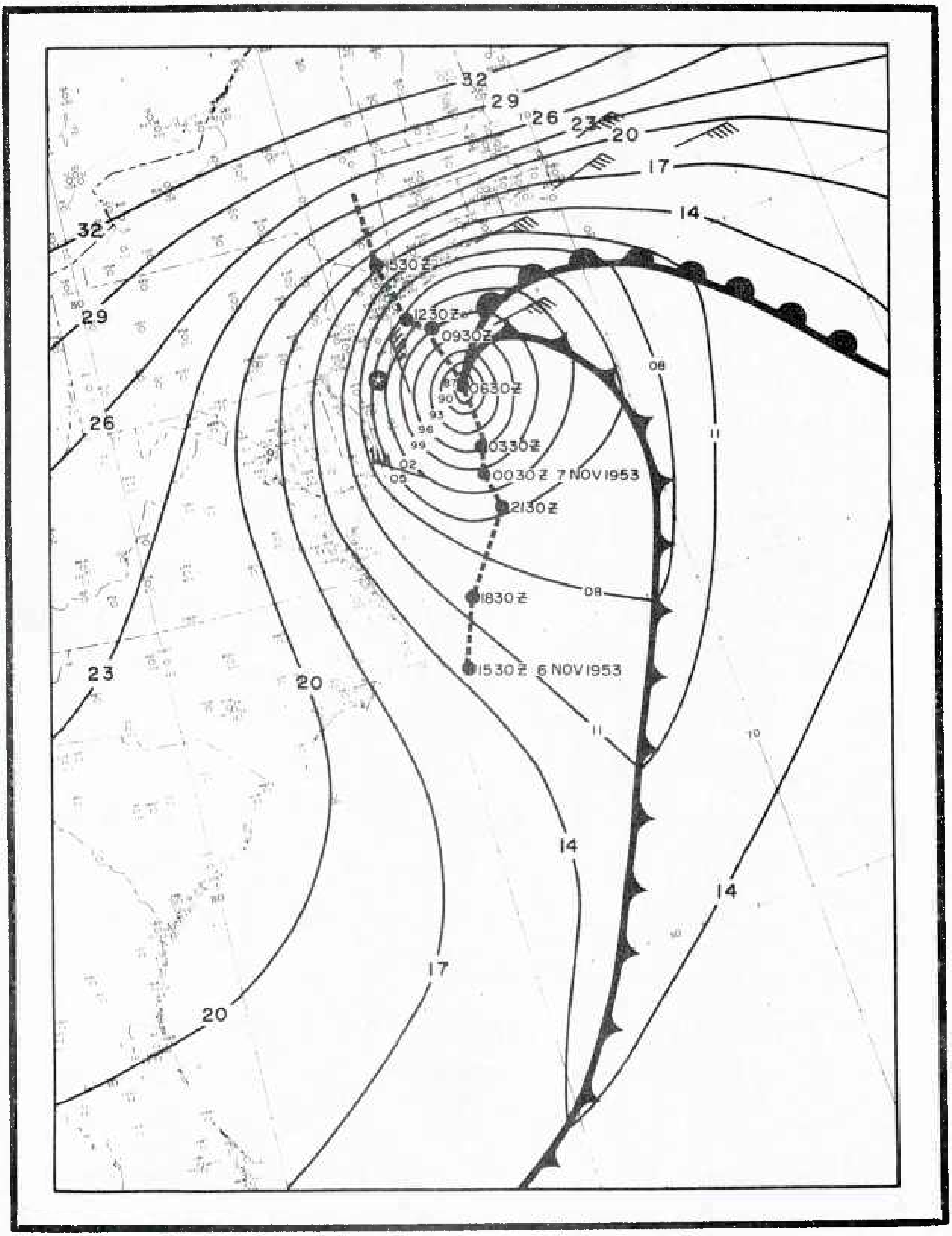


Figure C-2. Extratropical Storm.

choosing the outer pressure value, one must choose the pressure from the last isobar that is involved in the storm circulation -- which in this instance appears to be 1017 mbs. The center pressure was extrapolated to be 984 mbs., giving a sea-level pressure drop across the storm of 33 mbs.

The precomputed peak-storm surge h_s is determined from figure B-1. By entering with the CPA, 60 miles to seaward, and the storm's speed, 12 knots, the peak precomputed storm surge of 4 feet may be read from the ordinate scale.

Determining the Wind Field Correction Factor V_R is straight forward, and the F_D correction may be read directly from figures 17 or D-3. These parameters are entered into the corrected storm-surge equation, as shown on the check-off list at the end of this appendix, to obtain a corrected storm surge h_c of 1.4 feet. Wind stress and wave set-up (as shown in fig. C-1) could easily account for the remaining water height, to produce the 4.0-foot storm surge shown in figure C-3.

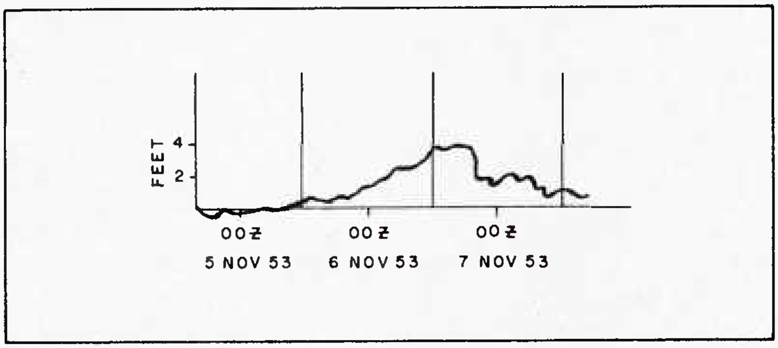


Figure C-3. Storm Surge at Atlantic City, 5-7 November 1953.

STORM-SURGE FORECAST CHECK-OFF LIST -- NON-LANDFALLING STORMS

A. From the weather maps

(1) Forecast the storm track to determine the closest point of approach (CPA) to the locale for which the prediction will be made. CPA ___60___ n.m.

(2) Forecast average storm speed. ___12___ knots

(3) Forecast the average 12-hour sea-level pressure drop. ___33___ mbs.

B. Enter figure B-1 with the CPA and storm speed; read the peak-surge height for a standard storm h_s. h_s ___4___ ft.

C. Enter figure 16 with a 30-mile radius of maximum wind and the mean sea-level pressure drop of the storm; read Wind Field Correction Factor V_R. V_R ___58___ knots

D. Determine Depth Profile Correction Factor F_D from figure 17 or D-3. F_D ___0.81___

E. Solve the storm-surge equation for the computed storm surge at the inner standard-basin boundary.

$$h_c = h_s \left(\frac{V_R}{87}\right)^2 F_D$$ h_c ___1.4___ ft.

$$= 4 \left(\frac{58}{87}\right)^2 0.81$$

$$= 4\ (.44)\ 0.81 = 1.4 \text{ ft.}$$

F. Based upon local conditions, add the following factors as appropriate to arrive at the storm-surge forecast. Wind stress and wave set-up: 2 to 3 feet.

APPENDIX D

DEPTH PROFILE CORRECTION FACTORS

The Depth Profile Correction Factor F_D modifies the standard storm over a standard basin equation so as to conform to natural basins. The standard basin has a standard slope of 3.45 feet per nautical mile from an inner boundary of 15-foot depth. This standard basin with a standard slope is delineated on each of the depth profile correction factor graphs contained in this appendix. Thus, a slope conforming to this line would have a correction factor of 1.0. Slope profiles shallower than the standard slope would be greater than 1.0, and those steeper than the standard slope would be less than 1.0.

Unfortunately, natural bottom slopes are far from uniform, as is shown in these figures where the plotted slope profiles make use of the latest available bathymetric data. The correction factors F_D have been deduced from trial runs for various model storms [43, 44]. The trial runs show a bias toward shallower depths, with most of the F_D factor being influenced by the slope within 20 miles of the inner boundary. This is well illustrated by comparing Cedar Keys and Key West in figures D-1 and D-3, respectively. The Key West slope is flatter than Cedar Keys beyond 20 miles and depths off Key West are shallower beyond 33 miles; but the correction factor F_D for Cedar Keys (1.72) is greater than

that for Key West (1.30). Slope profiles for selected U.S. Middle Atlantic Coast points are presented in figures D-5 and D-6, with the correction factor given at the end of the depth profile.

The correction factor at a given location depends mainly on the depth profile but also in a smaller way on the latitude. The values in parentheses (F_x) in the figures are not corrected for latitude whereas the other numbers F_D have this correction applied.

To develop Depth Profile Correction Factors F_D for points in other areas, a depth profile from the 15-foot depth seaward must be plotted in a manner similar to that shown in this appendix. The depth profile for the new geographical location is then compared with the plots in this appendix. If the new profile does not differ greatly from the slopes presented here, then one can interpolate between the given F_x (values in parentheses) to obtain the desired F_x Depth Profile Correction Factor. The latitude correction is then applied to obtain F_D:

$$F_D = F_x\ [1.0 + (.003)(\phi - 30)]$$

where ϕ is the latitude.

Correction factors for the selected points along the Republic of Vietnam coast shown in figure D-7 have been interpolated in figures D-8 and D-9.

Coasts that fall off sharply, such as between Quang Ngai and Cam Ranh Bay, are beyond the scope of the storm-surge prediction method described in this publication.

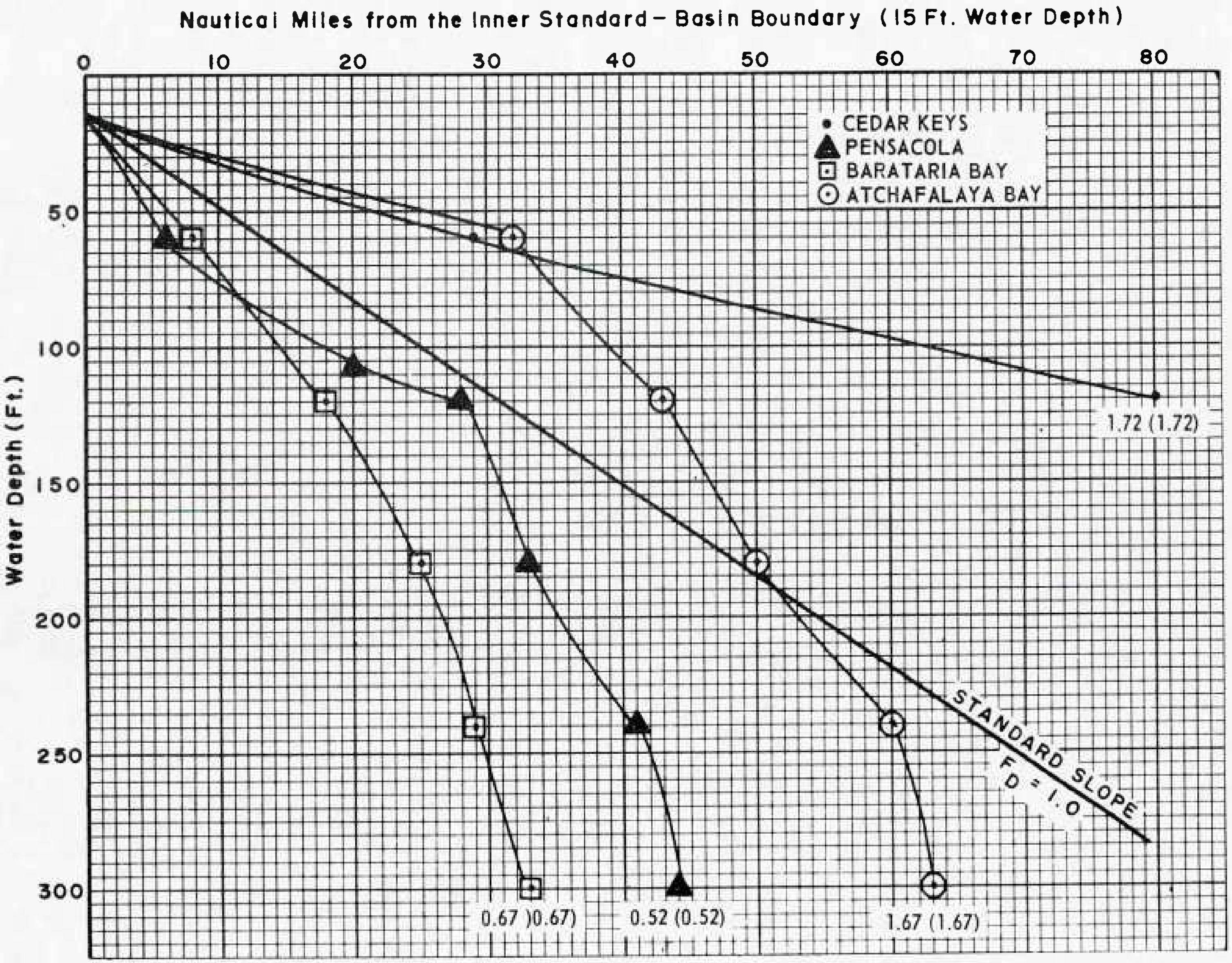


Figure D-1. Slope Profiles With Correction Factors for Selected Gulf Coast Points.

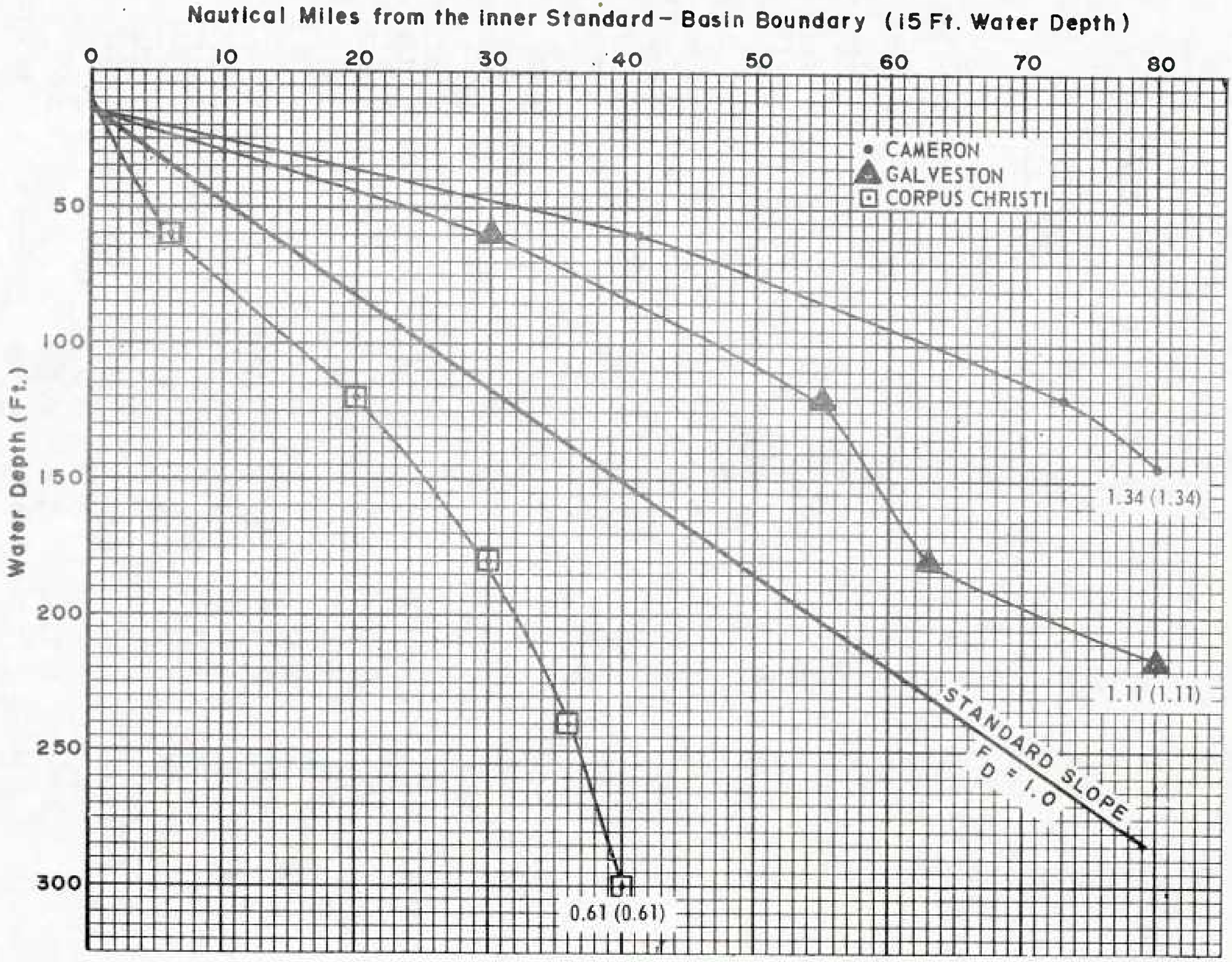


Figure D-2. Slope Profiles With Correction Factors for Selected Gulf Coast Points.

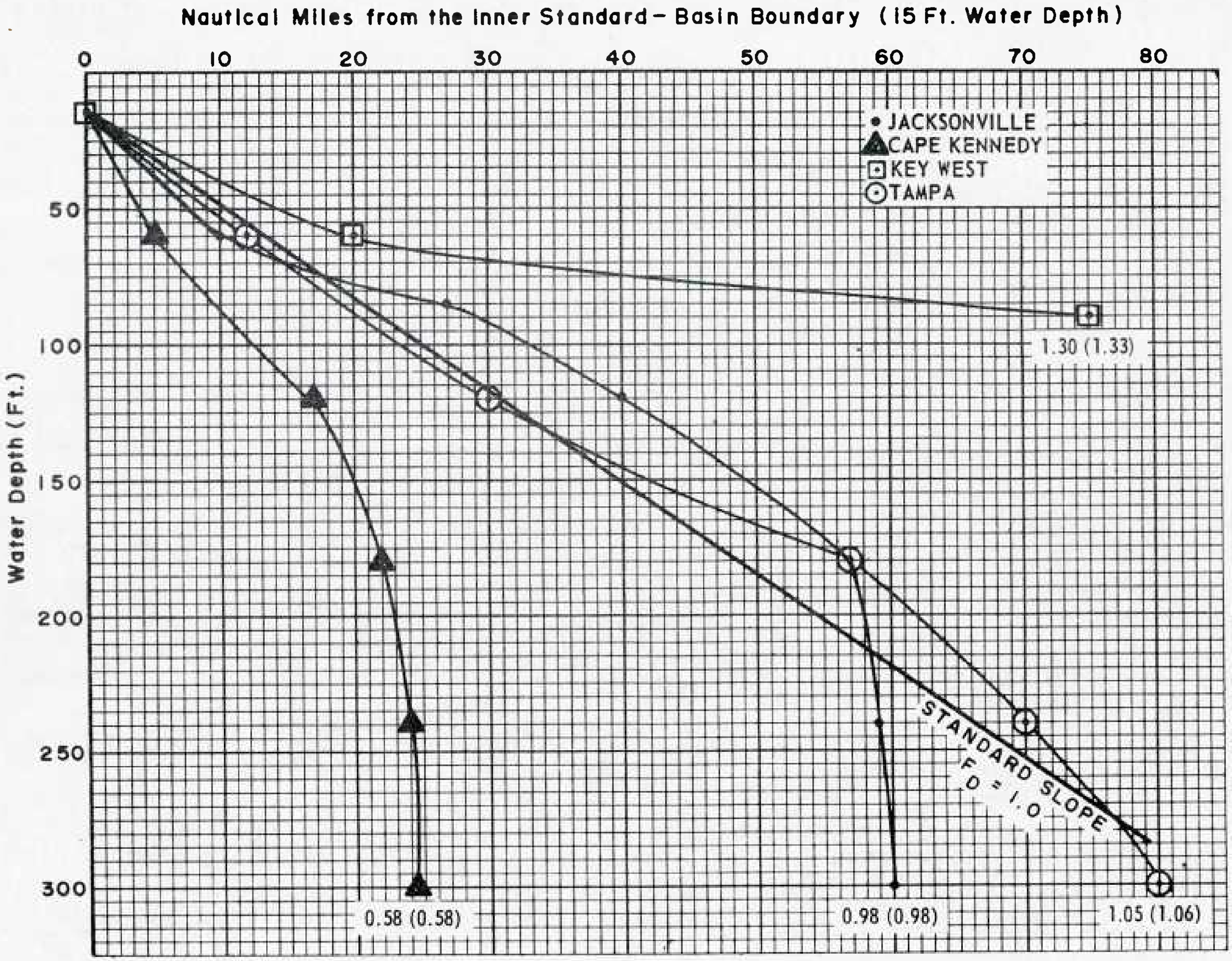


Figure D-3. Slope Profiles With Correction Factors for Selected U.S. Southern Atlantic Coast Points.

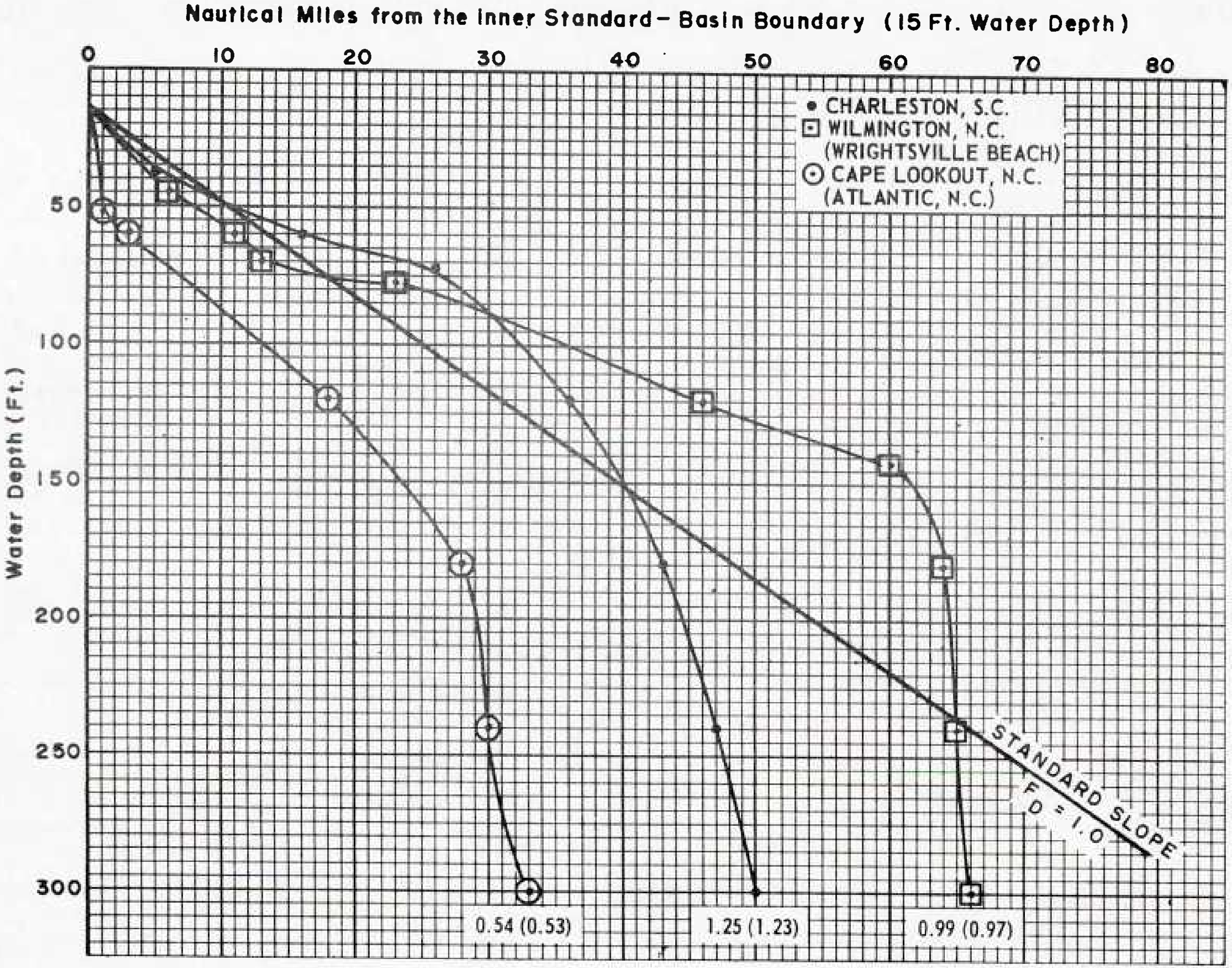


Figure D-4. Slope Profiles With Correction Factors for Selected U.S. Southern Atlantic Coast Points.

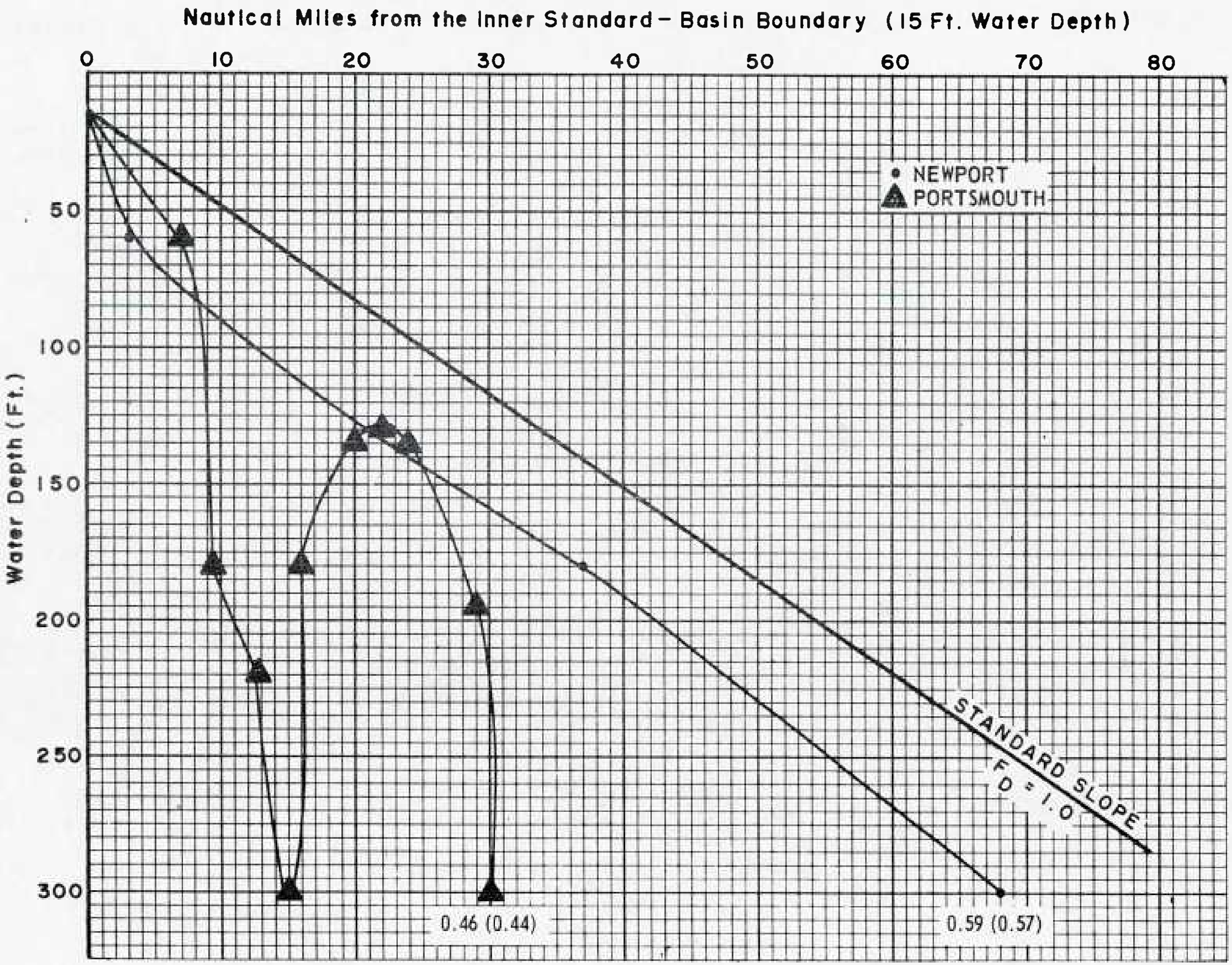


Figure D-5. Slope Profiles With Correction Factors for Selected U.S. Middle Atlantic Coast Points.

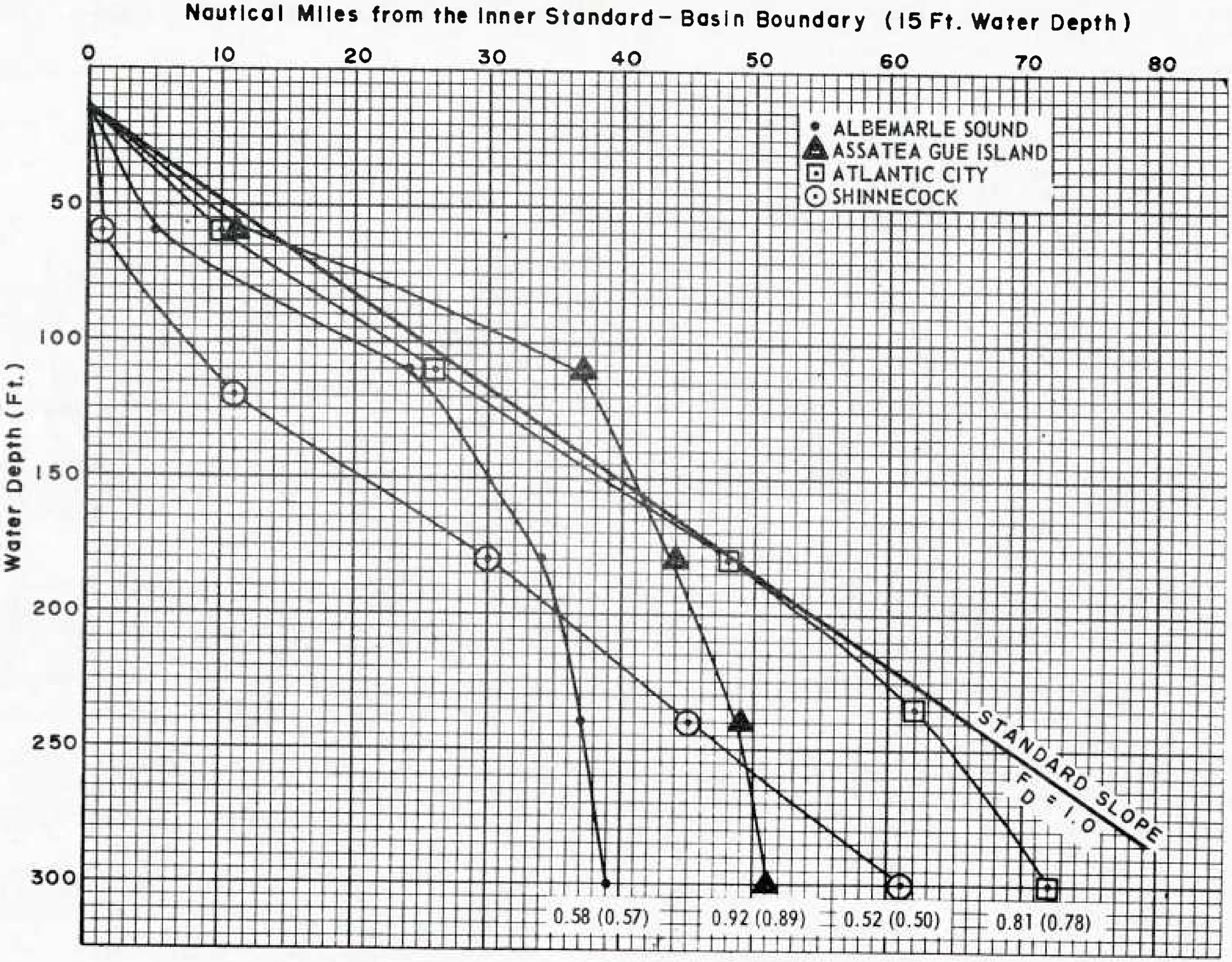


Figure D-6. Slope Profiles With Correction Factors for Selected U.S. Middle Atlantic Coast Points.

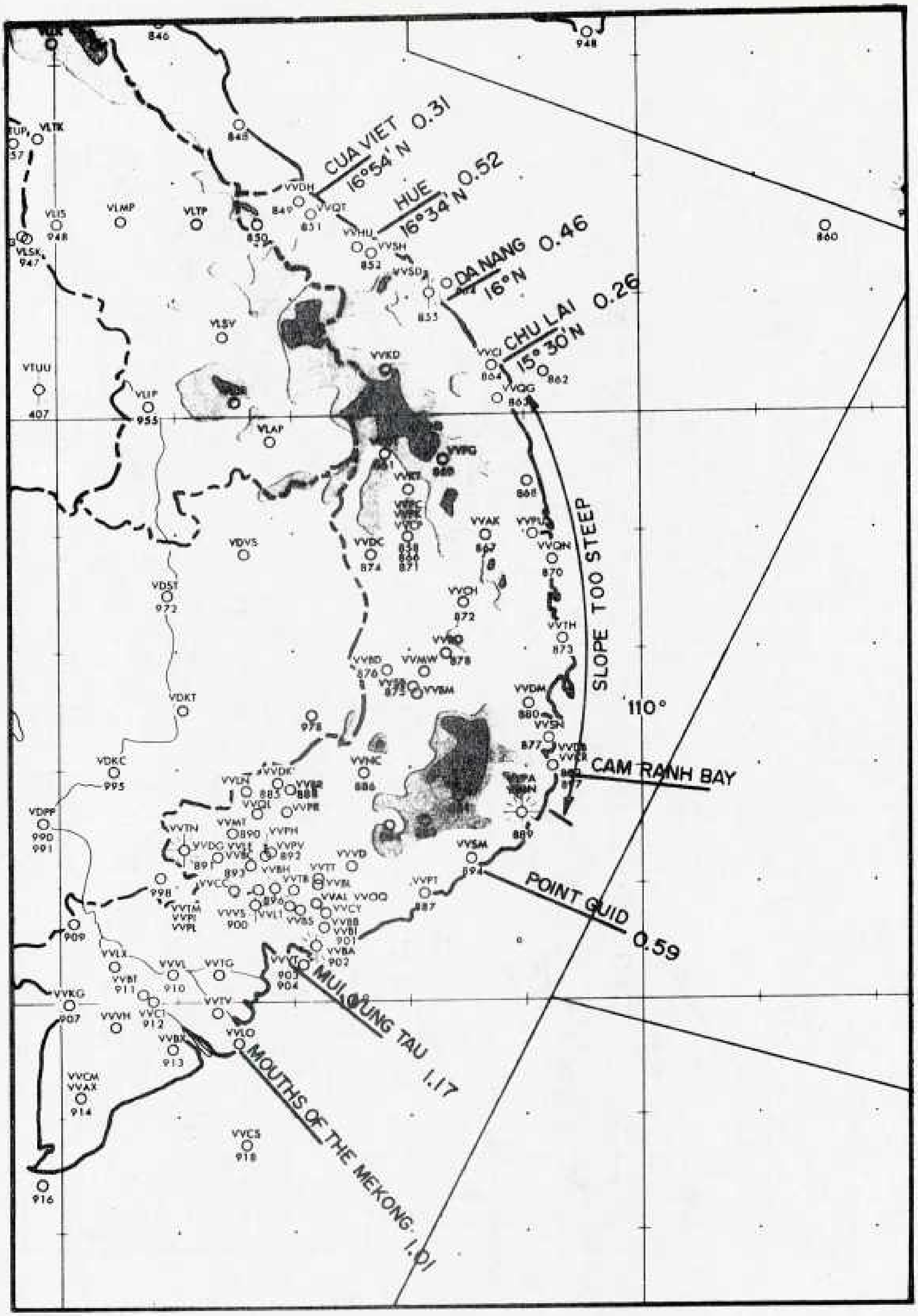


Figure D-7. Depth Profile Correction Factors for Republic of Vietnam.

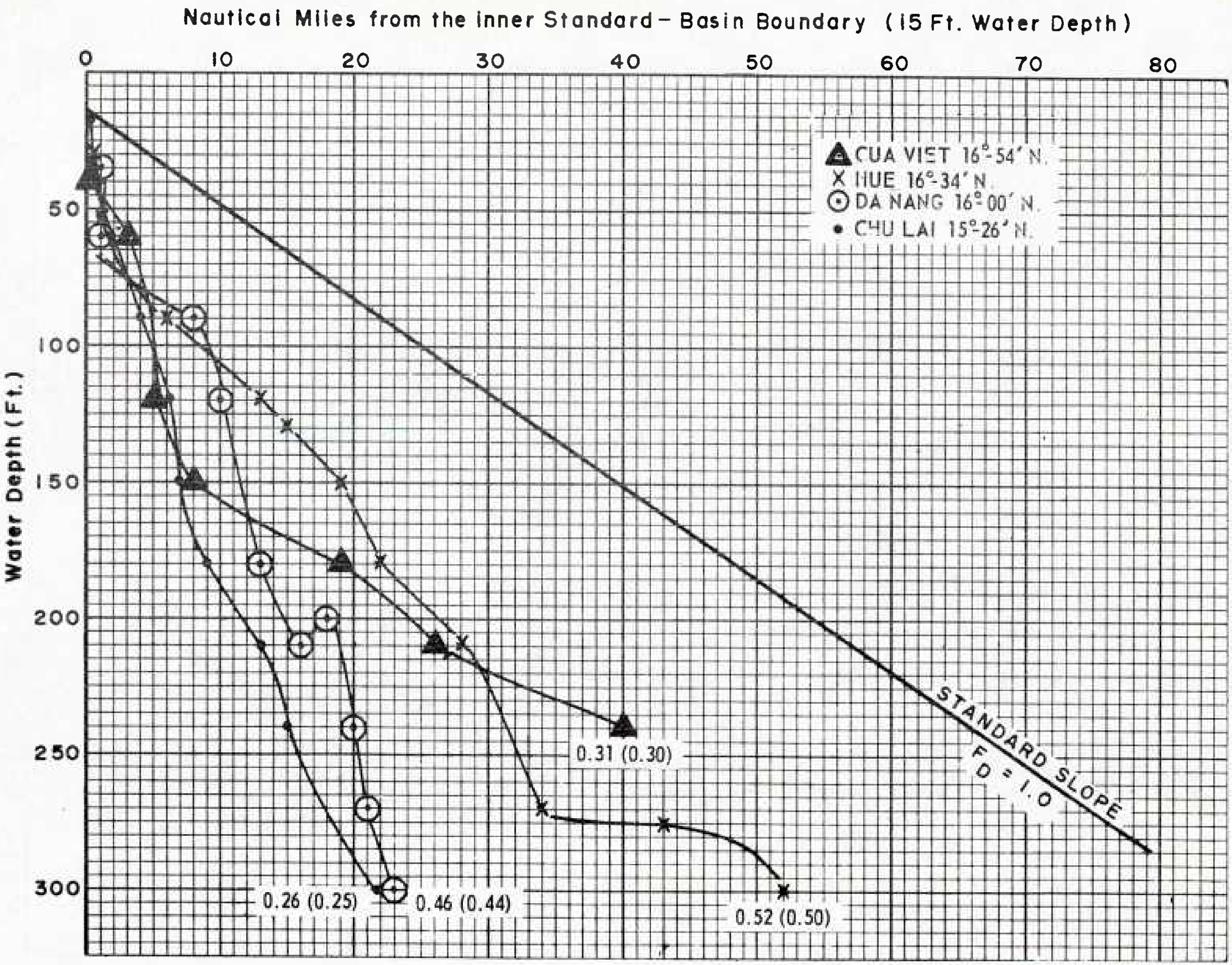


Figure D-8. Slope Profiles With Correction Factors for Selected Points Along the Southern Republic of Vietnam Coast.

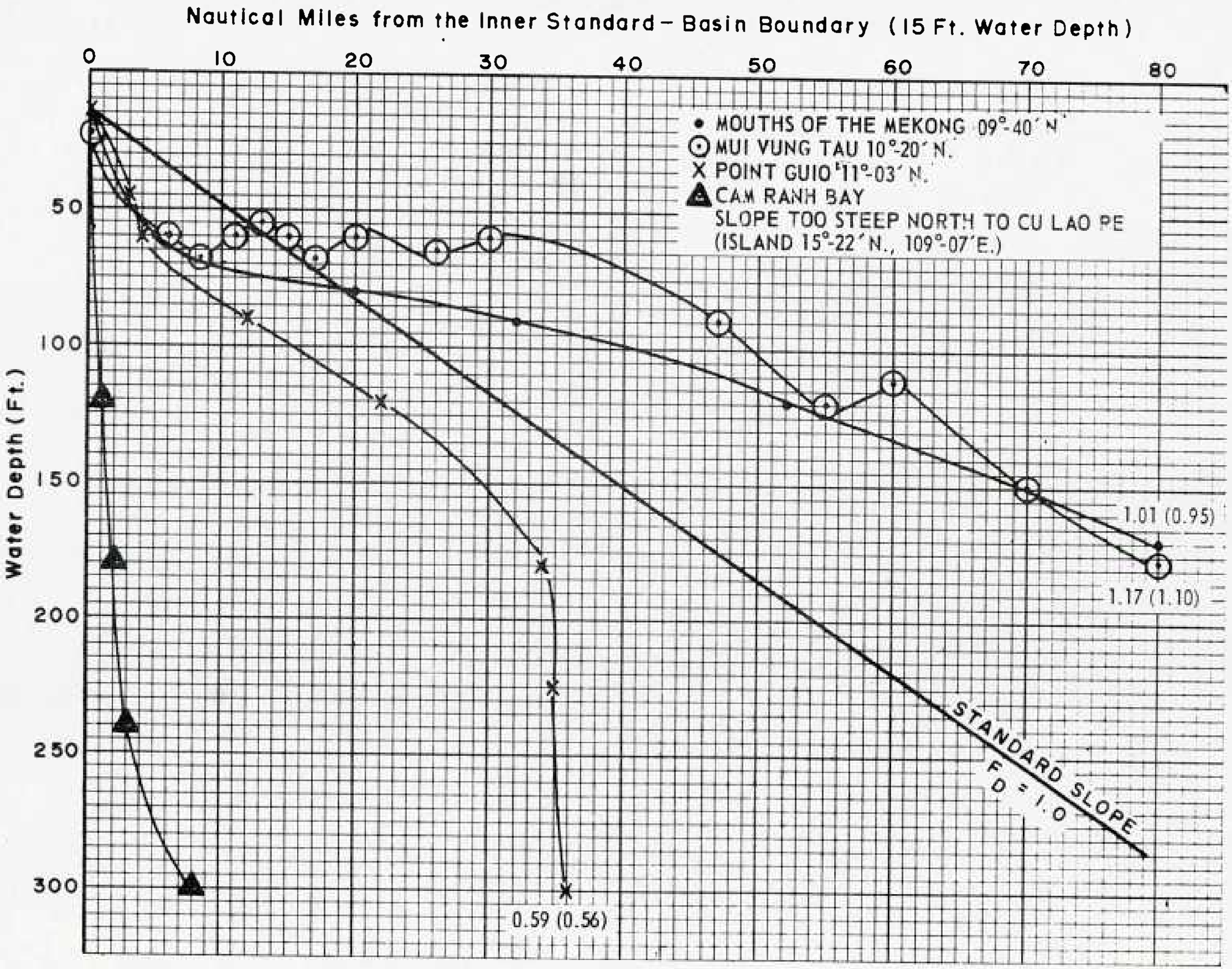


Figure D-9. Slope Profiles With Correction Factors for Selected Points Along the Northern Republic of Vietnam Coast.

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